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Decision Information For Tactical Command And Control

Held at Airlie House, Airlie, Virginia
22-25 September 1976

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PREFACE

Pared defense budgets are a particular challenge to maintaining supremacy of United States and allied forces against potential adversaries. With the qualitative superiority of our tactical weapon systems being eroded by mushrooming growth in Soviet military capabilities, consideration of the ways to employ military resources effectively in combat has risen to a par with considerations of the quantity and quality of the resources. Supporting the commander in maximizing the effectiveness of combat capabilities involves a full spectrum of activity which includes situation monitoring; formulation and evaluation of response options; execution of plans; and assessment of attack, damage and residual capabilities. With the military commander at the conflux of this spectrum of activity, combat information and decision-making processes unify traditionally separate military functions such as intelligence, reconnaissance, surveillance, planning, control, attack and attack assessment. The decision-making process has a voracious appetite for information — an appetite that in culmination must be at least selectively satiated toward sustaining the commander's ability to favorably terminiate hostilities and active operations.

One of the objectives of the workshop was to provide the managers of the Service Offices of Research with the knowledge that will allow them to formulate research programs relevant to military problems in decision information. Included in this objective is the presentation of scientific disciplines that have not previously been applied to such military problems next page

but which have high promise of yielding useful results. Besides presenting current research, it is hoped that the workshop will stimulate new research in the scientific community both in new areas and in the application of current work to military problems.

Four major objectives of the workshop have been identified:

1. Problem Identification
2. Enhancement of Interaction Between Researchers and Managers
3. Consideration of Operational Effectiveness Measures
4. Stimulation of Relevant Research

To identify specific problems in decision information, a number of military officers from various services spoke at the workshop. In addition, the numerous military participants in the workshop were able to comment on numerous operational experiences and problems, as well as discuss the application of various scientific research to these problems.

The problem of enhancement of interaction between researchers and managers was addressed by numerous participants. The directors of research for the military as well as the liasons for numerous research organizations contributed their first-hand experiences. Others in either the research fields or the military spoke to the problems of interaction from their respective points of view.

The consideration of operational effectiveness measures led to discussion not only of benefit-cost analysis, but also to work in situation assessment analysis. Considerable new research of relevance to this field was presented.

The stimulation of relevant research was, of course, a pervasive aspect of the workshop. This was particularly stressed at the conclusion of the workshop when many of the participants spoke directly to the relevance of the presented research as well as to areas deserving additional work.

The first day of the workshop consisted mainly of presentations by military officers. After an introduction by Dr. William L. Lehmann to the problem area, Major General Jasper A. Welch gave an overview of the problems and highlighted areas of particular interest. Rear Admiral Donald D. Engen spoke from the Navy's viewpoint and particularly stressed the role of the JCS. Lt. General W. L. Creech highlighted many of the particular problem areas both for the military in general and for the Air Force in particular. Rear Admiral George E. R. Kinnear then addressed some of the problems of the Navy, including some particularly relevant examples.

Included in the first day's presentations were models of Dr. Thomas Saaty and Dr. James G. Miller. Both presentations evoked lively discussion. These were followed on the second day by the presentations of the statistics panel. Included among these were the work of Dr. S. Zacks on inventory scheduling and Dr. H. O. Hartley on statistical PERT analysis. Also among the second day presentations was such work as that of Dr. John A. Modrick on decision support and Dr. Clinton Kelly on decisions analysis. The latter part of the second day was devoted to case studies, including a very interesting paper by Col. T. Thompson on interoperability.

The last day of the workshop began with papers by Dr. Thomas Saaty and Dr. Clyde Coombs. The lively

discussion that followed Dr. Saaty's presentation on the first day was continued. Also in the last day were the presentations by the general systems panel, including Dr. Robert Kalaba, and the operations research panel. The operations research panel included discussion by Dr. Seth Bonder, Dr. G. Bracken, and Dr. J. Dockery. There was also a thought provoking discussion following Dr. M. Sovereign concerning a proposed curriculum for work in the area of C^3.

Overall, certainly some of the workshop's objectives were met. The participation of the military both in presenting papers and during the many discussions definitely contributed to the definition and formulation of many of the problem areas in decision information. Similarly, the problem of enhanced interaction between researchers and managers was approached throughout the workshop. The relevance of many of the areas of current research was examined. In some cases, this led to new areas of application and in some cases it suggested courses of future research, either in the form of modification of existing work or in entering totally new areas. The need for future meetings was pointed up, both in a formal setting such as this workshop and in an informal way among the participants.

The editors, on behalf of all the participants of the workshop, would like to express their gratitude to the management of Airlie House, where the workshop was held. Their gracious hospitality and lovely surroundings greatly increased the overall enjoyment of the workshop. We also wish to express our appreciation to Dr. Ismail N. Shimi who was AFOSR Project Manager for the contract [F44620-76-C-0131] under which this workshop was funded and to Lt. Col. E. H. Ramirez, also from AFOSR, for his handling of protocol matters at the workshop.

The talk by Rear Admiral Donald D. Engen was not available for inclusion in these proceedings. Also, the remarks by Dean Harvey M. Wagner were based in part on a paper which will appear in a commemorative volume to be published as part of the Office of Naval Research's 30th anniversary activities.

The editors would also like to make two notes concerning the proceedings. (1) We felt that the impromptu discussions following the presentations constituted an extremely valuable part of the conduct of this workshop. Therefore, these discussions were tape-recorded and transcribed. Due to various technical difficulties, we acknowledge that there may be errors in these transcriptions. We apologize for this, but include the transcriptions for the considerable benefit they still retain. At times, the discussion became so animated that it was difficult to identify the speakers. When the identity of the speaker was unclear, the statement is attributed to <u>Question</u>. (2) In the interest of prompt publication, the papers here have not been refereed and aside from minor changes appear here as submitted by the authors.

The program and attendees of the workshop are given in the appendices at the end of the proceedings.

The editors wish to thank all of the individuals who, in addition to the speakers, contributed to the success of the workshop. A special thanks is due to the following participants for their kind assistance:

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We would also like to express our appreciation to Ms. Mary-Deborah Forbes and Ms. Diane W. Mabe for their kind assistance during the progress of the workshop. Finally, we wish to gratefully acknowledge the excellent help we received from Ms. Sherrie L. Dominguez, Ms. Wanda Balliet, and Ms. Linda Miner during the preparation and typing of the proceedings.

Robert M. Thrall
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I. THE PROBLEM OF COMMAND AND CONTROL

WELCOMING TO THE WORKSHOP

by DR. WILLIAM L. LEHMANN
Director, AFOSR

I am happy to welcome you to this workshop on Command and Control. It represents the unusual for us in Defense research in several respects. First, it is unusual because it does not bear a familiar research label such as Physics, Chemistry, Math, Mechanical Engineering, etc. Command and Control is not widely recognized as a research field, but its problems clearly can and must be addressed by research. Second, it is unusual because we have here today both research professionals from the government, academic and industrial world and military professionals from the services who have experienced and understand the real world in which our tactical forces - land, sea, and air - must operate. Third, some will perceive it as unusual in that we have three services cooperating to address this problem. But, if we are to meet the challenge of the Tactical Command and Control problem, we must depart from the usual and accept the unusual, perhaps even the radical.

This workshop has its genesis in a speech delivered by General Jasper Welch to the Aerospace Sigma Xi Club in 1975. I took three conclusions away from that speech. These were:

(1) Research must tackle the big problems where a solution would have a major impact on the way the Air Force operates.

(2) Research must marshal or create the capabilities and disciplines necessary to attack those problems. Too often research has accepted only those problems that fit the existing organizational structure of the established research community.

(3) Research must understand the problem as it exists in fact and must produce a product that is recognizable

and useful to those who must deal with that real problem.

Today, one year later, we are involved together in an experimental workshop. It begins with statements of the operational problems by authoritative representatives of the services. Program managers from the services next describe the current development programs that are addressing these problems. Finally, members of the academic and industrial research communities will describe ongoing research they believe to be applicable to the stated operation problems. We hope to create new research programs that will let us both understand and solve our problems. We recognize that we may fail in this objective but failure to try would be inexcusable.

This Workshop is sponsored by the Joint OXR's of the three services - the Offices of the Army, Navy, and Air Force Research. Much of the leadership and insight has come from the Studies and Analysis communities of the Services. This is a partnership that should continue and should grow. It is therefore fitting that our keynote speaker should be the Air Force's Assistant Chief of Staff for Studies and Analysis, Major General Jasper A. Welch. I am proud to introduce General Welch.

SOME RANDOM THOUGHTS ON C^3

by MAJOR GENERAL JASPER A. WELCH, JR.

Confusion Reigns, But Help Is On The Way. I'm going to talk about a lot of diverse and unrelated matters. You may ask what the theme is...and the theme is that I'm fairly confused. Now, another solid introductory remark is that my military colleagues addressing you later this morning and afternoon are officers with real operational experience. and they will tell you about how C^3 is in the trenches and on the battlefields. I guess that the only analogy to what I'm going to talk about now is the trenches of the Pentagon. I'm going to make a valiant attempt to describe those Pentagon trenches, because there are some real problems there. I'd also like to say hello to a number of old friends here - including some I didn't actually think to have invited but got here anyway...and I'm delighted about that.

Some Valuable Work Has Been Done So Far. My own particular interest in the evaluation of an alternative C^3 information structure started back in the late 60's when I became aware of a piece of work done for the Navy. When my staff researched it last week, we found out it was sponsored by ONR[1/] - by Dr. Martin Talcott, who, I'm glad to say, is here. His work covered the question of alternate C^3 support for an ASW[2/] task force. It was an explicit simulation of the flow of sensor data through a Combat Information Center. Then, somewhat later, I wound up being involved in the WWMCCS[1/] architecture study. I remember particularly because, in my case, I didn't know anything about the C^3 business, but I had become involved in the war plan policy-making business, and that impacted on the functions of WWMCCS architecture. I

C^3 - Command, Control, and Communication

1/ ONR - Office of Naval Research

2/ ASW - Antisubmarine Warfare

learned a lot from watching that activity over a period of time. (I understand we are going to have a talk on lessons learned by that particular activity.)

We tried to get Tom Belden here because he's a very interesting guy. Tom works in the CIA. Unfortunately he could not be with us; but, just the same, I wouldn't want you not to know about Tom. After he became interested in crisis management, he did a case study of Pearl Harbor. As you know, there is a very good unclassified version of that study by Roberta Wohlstetter Anybody who's serious about the C^3 function in that particular context really ought to read her book.

Tom has done some very interesting and innovative things in Washington. One of the most interesting things he did is establish a real-time network of secure communications within the Washington area among the watch officers of the various intelligence agencies...for the staggering price of $2.50. It was a job everybody said couldn't be done, and we were definitely not willing to allocate a reasonable budget to it simply because it wasn't possible. Tom thought about it for a while and figured out that the problem was that things were a little too big... and that all it took was five toggle switches.

I am also particularly pleased that we will hear from Colonel Thompson from the Tactical Air Forces Interoperability Group. Their work in describing a well-known "monster" C^3 system is especially interesting.

"Jet" Technology Versus "Horse and Buggy" Communication. The current widespread interest in tactical C^3 arises from a number of ongoing changes. We'll talk about several of them. One that I think is really bothersome to me as a human being is the increased rate of application of firepower - the rate at which firepower can be applied. A consequence of this is that the disposition of our forces and capabilities can change faster than the rate at which people are prone to make a reevaluation of the

1/ WWMCCS - Worldwide Military Command and Control System.

situation.

It takes most of us several hours, if not several days - or for the difficult situations, several weeks - to begin to get an appreciation of the fact not only of what has changed, but even that change has taken place. With the growth of modern munitions and high-speed delivery of weapons of all sorts, we become increasingly aware of a distinct possibility that the world can change before those in charge of it can know that. That's a fundamental gap that can really generate chaos - in the Biblical sense. (This is a far cry from the war of 1812, when the war was over for a month before one of the most interesting battles was fought.)

Yes, Politics Do Fit Into the Military-Operations Picture. Another thing that I would like to call to your attention for background reading is an article in the April 1976 issue of World Politics which is a case study of the failure of national intelligence estimates in the 1973 Yom Kippur War.[1/] It has a fair number of lessons learned. One of which is that in retrospect (i.e., Monday morning quarterbacking) there were certainly adequate signals present. The problem was that there was a lot of noise as well. There was noise not only in the external communications channels in the case of the Yom Kippur War, but also within the minds and hearts of the players - that is, they didn't want the war. Their predisposition to interpret the external events in terms of a predisposed desire (a very common interference in thinking) in fact led to a very serious error in judgment and to the very near tragedy in the events of the world at large.

This whole question of trying to drag out the real meaning of events in the political sense is with us all the time. In

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1/ Avi Shlaim, "Failures in National Intelligence Estimates: The Case of the Yom Kippur War," World Politics, April 1976- Princeton University Press: Princeton NJ.

military operations, a lot of people try to dissociate and try to say, "That's a different subject." I don't think it is a different subject, because they both involve the human race.

I think we could also learn a great deal from the study of crisis management (in nonmilitary affairs) which is very commonplace - that is, the kind of risk-taking in our everyday lives and the kind of risk-taking people do in other areas where they feel a responsibility for their families and their business.

And Let's Not Forget Cultural "Set." There also are very substantial cultural problems. We have, for instance, engaged in a number of political/military war games where people are faced with artificial crises and asked to guess what actions they might take. You can sometimes play two-sided. One finds that guesses have a very different flavor, depending on whether the various sides operate within the cultural norms of the countries they are representing. The cultural norms very much color the kinds of activities one might want to concentrate on. Western nations by and large, when faced with a crisis, try to solve the problem as soon as possible. Other cultures want to try for a long-term solution. They merely avoid the disaster of the near term, while permitting the flowering of some favorable outcome in the long term. So in trying to establish what kind of C^3 system you want, it's important to know what kinds of backgrounds the participators are coming from: that is, not only their formal training, but the kind of world societies they come from.

Enter "Role Division." There are a couple of other things that I'd like to talk about. I find it useful to describe what the air arm does in the following three simple tasks:

- Deliver ordnance on target.
- Deliver perople and material.
- Collect, process, and disseminate information.

The first task has to do with either air or ground targets. The second has to do with logistics and airlift. The third is more pertinent to exactly what we're here for - the process of

gathering information.

In the Air Force in particular, quite a bit of its budget goes to the selective processing of information directly for the Air Force. On the other hand - through a combination of random events in the past - a great deal of the Air Force budget also goes to support services for other customers. Some of it is laundered through the Air Force budget, and we have more or less direct control over it. A lot of Air Force people, even though they're not in the Air Force organization, are involved in this.

This brings us to the prime activity in the trenches of the Pentagon - to decide whether or not that money is being well spent.

The classic delivery-type missions (the first two) have been subject to a great deal of budgetary controls, and a great deal of work has been done on how to tell whether that type of delivery system is doing its job. Although there is a great deal of controversy remaining, there are well-developed disciplines of analysis and of decision making, and well established criteria (even though there are alternate criteria). The controversies are really a matter of choosing between several well-defined alternatives.

Why Are Budgets Up When Costs Per Bit Are Down? By contrast, in my view, the question of resource management in the C^3 area is almost out of control. There are no universally accepted descriptors or criteria suitable for use in the budget-decision process. The increases in funding for C^3 and information matters continue to rise in spite of the fact that the costs per bit of collecting and assembling data have been subject to enormous reductions in the past 10 years. In spite of the fact that the cost to perform a given operation has improved due to an explosion in technological capabilities unheralded in any other technology, we're actually spending more.

You may remember in airframe development work where you might get a factor of two in productivity in a decade. In the

C^3 information-processing situation, the net cost per bit of information processing has gone down by a factor of 10 in each decade over the last four decades. In spite of that, we're spending more. Obviously we're trying to do more. (We're certainly churning more.)

It seems to me that, from sheer horse sense and brute politics, the dollars allocated for the C^3 process is within a factor of two of what it is ever going to be.

There are several reasons why the current state is the way it is. I already mentioned the absence of agreed-upon criteria. Another problem is purely sociological: That is, that the hardware builders today operate against a separate, administratively controlled community. What the requirement community says it needs, the hardware builder is more than happy to supply. That interface occurs along a ragged line within the bureaucracy; but nonetheless you can always find it.

Even the requirements community can be reasonable responsible as long as they understand that if they buy <u>this</u>, they cannot have <u>that</u>. It is my fiew that the requirements community in C^3 has not explicitly had direction in this area. The reason why they are able to simply respond to requests is that for many years the C^3 costs amounted to a small fraction of the total budget. The immature technology of the past produced self-regulation. For example, there was just so much you could do in the way of HF[1/] radio because there was only so much bandwidth; and people had long ago filled it all up. So the technology itself was self-regulating. That's not true anymore. As a result, we have this great explosion.

<u>Breaking C^3 Down Into Functions: For Clarity</u>. I have found it very useful to break down functions in theater operations. the following list relates primarily to offensive operations.

1/ HF - High frequency.

The individual items range from large, aggregated ones to the more specific. I present this because of the confusion when different people think about different functions, but they call it all C^3.

Some people talk about fire direction. Fire direction is what the control theory people worry about, by and large; that is, how do I guide a guided missile to a target I have it locked-in on? That in itself is a very large and fairly well-developed system of theory.

Target development is an Army term which you may be familiar with. It's a question of looking out across the landscape and deciding which things are worth shooting artillery at, and finding out where they are, and trying to keep track of them.

We tend to forget that the ICBM world has an enormous target-development program associated with it. Some people know a lot more about these programs than others because of certain intelligence-compartmentalization problems. But, in general, unless you have a good idea of what your targets are, it doesn't make any difference how good your fire direction is.

There are questions of allocation - of allocation of weapons to targets and of allocations of forces to operations. How many divisions do we send into the Normandy landing and how many do we pull off southern Italy? How many riflemen to send to the right flank and how many to the left flank?

The Air Force is very much involved in the question of allocation of forces to military operations, because airplanes can go to several different locations and can do several different things. But they can only fly one sortie at a time.

The allocation problem has been taken to great lengths. In allocation theory there are very well-developed theories that are useful. One of them (which has been around longer than I care to remember) is Lagrange multipliers. The trouble with Lagrange multipliers is that you need to know the underlying value structure, and that is what you don't know when you're making al-

locations to operations - because operations have a time dimension, and an interactive dimension.

In Military Operations, the Exploitation Phase Is Just As Important As the Set-Up and Strike Phases. In dealing with military operations, I like the book by Liddel Hart called Strategy.[1/] He is one of the world's leading military historians. In the back of that book is a striking insight about military operations. In his view there are three phases: the set-up phase, the strike phase, and the exploitation phase. Hart, quite rightfully in my view, complains that most people only worry about the strike phase. That's the easy part. The hard part is the set-up, to maneuver so that the opponent is off balance or overly dependent, so that the strike makes a difference. ...And then there's the question of exploitation.

Some exploitations are really rather obvious. If you make an artillery bombardment on the right flank, you ought to send your armored forces out more or less to the right flank to take advantage of the bombardment you did there. Nonetheless, in this year of the Bicentennial, it is well to remember that one of the reasons George Washington was so successful is that in the campaigns around New York City, the British General, William Howe, failed to exploit his initial victory each and every time. As a result of which, we <u>had</u> a Bicentennial this year. That was a classic case of failure to exploit a successful strike phase.

<u>Maneuver Can Also Be the "Message</u>." To some extent, many times in the past, failure to exploit success came about because the guy didn't know he had any success to exploit. The whole question of whether maneuver is more important than firepower, and vice versa, has filled the military history books. Modern C^3 will add complexity to the debate.

Before the age of the sensors and communication we now think

1/ Liddell Hart, Basil Henry, Strategy (New York, Praeger, 1967).

about, the only way to find out if there was a unit on the other side of the hill was to go over and see if anybody shot at you. If you didn't send a reasonable enough force, you still didn't find out because nobody came back - and you didn't know if everybody had gotten lost, had deserted, or had gotten shot. So, maneuver itself was an instrument of combat information.

The lack of detailed information at a distance in those days led to a lot of other fundamental battlefield phenomena. For instance, units began to feel encircled when they really weren't. The classic case of that is in Barbarosa where in the '42 campaign of the Germans against the Russians, there was a pincer movement in the vicinity of Minsk. The Soviet army of 300,000 people surrendered virtually without being shot at or having shot in anger themselves, because they perceived themselves to be surrounded with a double pincer involvement by the Germans. The reason they perceived they were enveloped was that they received telegraphic messages which said that all the cities and villages around them had "fallen" to the Germans. I suspect - unproven - that what had happened in a number of instances was that a lost German squad had wandered through and their vehicle had broken down. They couldn't go any further and didn't want to spend the night out in the fields, so they commandeered the local village chief's headquarters and sent a telegram.

Most Of Us Can Recognize A Reubens Much Better Than We Can Paint One. The facts are that the Russian army could have marched out of their positions in any arbitrary direction and they would have been lucky even to find a German, the Germans were so thinly spread in this envelopment. But they didn't do that, they surrendered. There was a case where the maneuver on the part of the Germans had an effect far out of proportion to its actual military possibilities.

To back that up again - all this has to do with "what is the situation?" (that is, situation assessment, relating again to the warning and indication system) and finally to the question we've

gotten very much involved in, the question of preplanning.

Military operations are complicated; and, to a large extent, you can only hope to do those things in war which you can practice in peace. You try very hard to practice building block-type operations which can be used to apply to the actual circumstances. Nonetheless, to the extent you have preplanned, to the extent that you know what you're looking for, you can get a tremendous amount more out of your information system because you're in the business of correlating it, not just trying to paint a picture out of the whole situation. Let's face it - most of us are a lot better at recognizing a Reubens than we are at painting one.

What the Computer Can Do, the Human Mind Can Sometimes Do Better. This whole notion about thinking through what it is you're looking for, and what you can do about it, is rather intriguing. It's the connection between how people think in their minds and how their combat information systems work in battle. Those processes, in my estimation, are completely entwined one with the other.

There are many people today who have done completely the wrong thing in a number of combat information systems - that is, they give given to automatic data processing those things that the mind does best, and vice versa. The organization of geometrically related information is, generally, quite easy for the human mind. It may be rather easier for some than for others, but there are quite well-developed psychological tests to sort those people out. And there are other things the human mind can do better.

There are some simple things that I see people not keeping straight. On the question of whether a piece of information is worthwhile or not, there are a number of tests in this context which things ought to meet. You'd be surprised how many dumb ideas get sorted out because they don't meet very elementary tests.

Give the Information the "Worthwhile" Test? The first and foremost test a piece of combat information should meet is: "Does it resolve a real ambiguity?" We ask not only is it information in the Shannon sense of resolving an ambiguity, but how big an ambiguity? You say the missile was successfully launched. Could it have been either way? Not really, because one has a tremendous amount of a priori information about the ensemble of all missiles; and, whether or not that particular missile was launched may or may not be an ambiguity worth resolving. If most of them go, then it turns out you really can't improve matters much by knowing which one didn't

Second, there is always a best thing to do if the ambiguity is unresolved. The question is: "Is the best thing to do that much better an outcome if you have resolved the amgiguity?" Can you do anything different - not even better, just different - after having resolved the ambiguity? That is worth checking.

In many cases, you can't do anything different. But the guy says, "Well, it will make the commander feel better." A lot of stuff is justified on the basis that it will make the commander feel better. So, is there even an alternative action? Does that alternative action result in a different effectiveness? Is there an alternative outcome? Is it a higher-order outcome? Now eventually, getting beyond that, you worry about action/reaction and trying to see if there is anything acceptable. Because after all, combat is an interactive situation.

Don't be dismayed because these fifth, sixth, and seventh levels are very difficult to carry out. You can generally throw out the obviously bad ideas way back at the first or second levels. But those levels are not systematically applied, and they are not systematically taught to managers.

Decisions, Decisions: Do I Act Now, Or Do I Use Up Precious Time To Get More Information? Lest you figure that offense is everything, there are some other activities related to defensive operations and support operations that I haven't thought through

so carefully. The first one I very much want to bring to your attention is the question of can you do anything on the basis of the information? One of the most important things for a command center to do is to decide whether or not to request certain other information. There is an opportunity cost in the time required to acquire this other information; and this is often used as a cop-out. There are numerous examples of people going down the tubes while waiting to find out what the situation really is. The question of asking for information to be collected is very important.

Guard Against Your Opponents' Smokescreens. Information-collection is particularly important to the Western Allies because our opponents have a policy of cover, deception, and disinformation. That is considered equal in their minds as an arm of warfare to tanks, guns, ships, and planes. To the extent to which you build yourself a combat information system and to the extent that you rely on it to improve the efficiency and effectiveness of your forces, you open up a flank.

That's always the sutuation in the military--that no matter what you do directly, you always open up a flank indirectly. The indirect flank that goes with betting on a combat information system is: opening yourself up to disinformation, cover, and deception--as well as interference in cutting the channels. So it's very important to recognize that and to arrange to be able to confirm the information's validity and decide what you're going to do about it.

You Don't Have To Disseminate the Information Just Because You've Got It. There's a bad set of words with regard to dissemination and filtering of data--as if that's all you do with it. It's a "quick" system--to disseminate data implies that the guy who has it gives it to someone else. I don't know how you decide when the "push" data and when to "pull" it--when you should order data and when you should disseminate it. It's a very complicated business; but, at a minimum, you ought to understand that there

are those two choices. Just because you have a bit of data doesn't mean you have to go tell everybody about it. Every time you do it, it costs money--and that's an opportunity cost. It may be useful just to have it; and if anyone wants it, that's fine.

You might say, "That's silly. I've gone to great expense to collect it and what good is is to have it sit around in any computer bank?" One of the reasons is that it may be cheaper for the other guy to collect it himself rather than to ask you, or for you to send it to him. That's one of the great myths in this business: if I've got it in one of my computers and I want to get it into another one, it's always cheaper to transfer it between computers. I see no evidence that that is the case. On the contrary, there are many cases where it's a lot cheaper just to recollect the data from scratch. You know that's true. For example, you let each rifleman aim at the target even though one guy knows where the target is, and he could tell all the others how to aim their rifles.

Is It a Black Zebra With White Stripes Or a White Zebra With Black Stripes? What people want to know about is the question of resolving an ambiguity related to their plans or to their anxieties. The first thing they want to know is: "Am I on track? Are things more or less right?" They want very small pieces and amounts of data which are the aggregations and the integrals and correlation functions over a lot of things. For a single set of data, different people want different correlation functions, different integrals.

The flow of great quantities of data serves a very useful purpose when you want to have, for example, two correlators looking at the same piece of data and comparing their perceptions. There is a case where they want the same data set available, physically, to two different correlators. They both know that their correlators are imperfect, and they want to compare the outputs, given the same inputs. "Do you see what I see?" One

says, "I see a white zebra with black stripes;" and the other says, "I see a black zebra with white stripes;" and the commander says, "You SOBs shoot him anyway!"

Combat Information Systems: Shadow Or Substance? One of my jobs is to proffer advice on whether or not one should spend money on a particular piece of hardware, be it airplanes or missiles or munitions. Occasionally, we get asked to do that about combat information systems. We don't do a very good job of answering that. A year ago, when I came to Studies and Analysis, 1/ we set out to collect several good people and gave them the job of getting better at that. They seemed to be doing pretty well.

However, suddenly, a few months ago, I had a terrible, terrible thought. That thought was that sooner or later, those guys were going to come up with a method--and I would be faced with the decision as to whether that output was valid enough to allow it to be entered into the real decision process. What tests could I apply? If the question were the value of an IR sensor, I would immediately know to ask about transfer functions and interference from outside forces and a whole list of things. But I don't know how to test a thing which alleges to evaluate a combat information system. Let me tell you how far along I am and the tests I am applying. It may occur to you that there are some other questions I should ask.

What Should a "C^3 Simulation" Be Able To Do? What we're going to have is a simulation of a combat information system. Here are the things that I think the simulation ought to be able to do:

First, it ought to be able to discern the range of logical future actions of the opposing force to carry out those actions. Can he encircle the left flank and is he likely to want to do so,

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1/ Assistant Chief of Staff, Studies and Analysis, HQ USAF (AF/SA).

given my current situation?

Second, the simulation should be able to plan the actions of the friendly forces such that if they were carried out, the inherent capabilities of the friendly forces would come into play. If I have a bomber, it ought to be able to plan a bombing raid in a way that utilizes the bomber's inherent capability.

Third, can the simulation control the combat intensity--the rates of engagement--in accordance with planned rates or intensities? One of the troubles with a lot of simulations is that they assume both forces go at it like two scorpions in a bottle, trying to maximize engagement rates. Rarely is that the objective in combat operations. The more general statement is that you plan on a rate of engagement and try to keep your forces on that plan.

Two other points are: fourth, the ability to control the movement and alert status of friendly forces in accordance with a plan or agreed-upon reaction, and fifth, the ability to function better if provided with more basic information or better or higher quality information or more timely information. You don't know how much more, but you feel that if you increase the information and the simulation does more poorly, there is some structural defect.

Anotyer text is, sixth, the ability to manage the protection and delivery of supplies and maintenance to maintain the inherent capabilities of friendly forces.

Then I thought of one test that may be very controversial. That is, seventh, the ability to accommodate and compensate for unexpected or unfortunate events, erroneous or missing data, or aberrant actions of subordinate or superordinate headquarters. You really wouldn't want to have a military operation where one bad decision could propagate and infect the whole organization. Most military arrangements have ways to keep that from happening...one of which is to fire the commander.

The final points are: eighth, the ability to exploit opportunities afforded by actions or characteristics of the enemy

forces and, ninth, the ability to achieve a proper balance of contributions to the overall C^3 among the headquarters appropriate to their status. For example, it was alleged in one simulation that there was input from Corps headquarters, but if you put in random numbers for the input from Corps headquarters, there was no change in the combat. That, I would think, would be an inappropriate balance.

Summing Up. I can only sum up such a random assortment of thoughts by sharing my overall motivation--that this assemblage of talented individuals from so many diverse fields can, over the next three days, provide a broader and deeper insight to each of us. I know, speaking as both a researcher and a government executive, that the hardware technology provides us greater promise than it has rewards--and I hope that somehow, working together, we can reverse that judgment.

DISCUSSION

Bonder: Why do you have to do better with more information?

Welch: Because more information costs money and my job is to decide whether it's worth buying the information.

Bonder: Why does the real world do better with more information? Why does the process behave better? In the real world, if you watch commanders making decisions, you will see that when more than a certain amount of information comes in, they don't use it. They just discard it.

Welch: I think that's true. It happens all the time. I'm torn because there are two things. I set that criterion up as a test for whether the simulation was rational or not. I did not want it to be the result of a structural defect of the model. Our current thought on how this effect occurs is built on this idea of correlation integrals. That is, one is providing more examples of the same wrong correlation integral at either too low an aggregation or too high an aggregation. Most of our thought processes now revolve around the question of what are reasonable correlation integrals for each headquarters. I think that, depending on the action you take, there are different kinds of correlation integrals.

Dockery: You had a rather interesting list of things with regard to simulation. Do you want the simulation to do these things while it is running or do you want it to play out the battle so someone can come along later and draw his own inferences.

Welch: I started the list for a very simple thing. When people brought me their test cases, I wanted to see if the simulation was even capable of doing those fundamentals. I had the notion that if it was incapable of doing that, it probably wasn't a rich enough and responsive enough simulation that I would be willing to say, "The simulation says that system A is better than system B". Clearly, this list can be used for different types of analyses. The answer to your question is a little bit

of both.

Henderson: I think you might want to check into a study I heard about a year ago in which people tried to do a simulation using people with operational experience as division commanders. The result was that from commander to commander the outcomes and decisions were very different.

Welch: I think that's a very exciting piece of information. It is our plan to allow-encourage statistical variation in decisions. Let me add to it the other extreme. Six years ago I saw a historical survey of armored engagements in the twentieth century. They plotted which side won as a function of force ratio . They found that indeed there was a correlation but it was very, very low. Even with a 3 to 1 advantage, there was some propensity to lose. By no means was it a high correlation between winning and force ratio. The lesson I drew was that better decisions or luck or terrain was a very important factor in the outcome. I think there is a mythological hope that part of the noise they saw was noise that could be corrected by better combat information. This is a couterexample.

Knight: I would like to make a few observations because you hit on intelligence in your talk. I think we should consider the role of intelligence here. It is obvious that intelligence plays a very important part in command and control systems. Without intelligence you don't know how to command and control your forces and you can't make optimal allocations. We have to make a distinction between information and intelligence. Information is unevaluated data which can produce intellience. Intelligence is predictive in nature. It evaluates what comes in, helps value that information. The primary function of the intelligence officer is to provide not only the information, but also the conclusions based on the information. There is a tradeoff between different kinds of information. Some information is of immediate value and must be communicated to the commander directly. The role the intelligence officer plays in this is to provide pre-

diction and fill in the gaps. To put this in perspective, I refer to the words of Gen. Bradley. "My intelligence officer tells me what I should do. My logistics officer tells me what I can do. I decide what I will do."

Welch: I did not use information in the way you referred to there. That is a classic and important distinction you made. But today because of the way bureaucracy has grown up, the classic intelligence community is in a very awkward position. There are large sources of both evaluated and unevaluated information over which the intelligence organization has no control. There are a large number of evaluative and action-taking organizations over which the commander has no control. Many of these are of the nature of an automatic guidance system. In many cases, in particular in aircraft operations, the commander is involved down to the pilot or a forward air controller who assumes control of a few airplanes for short time. I have used the word "Information" here to describe the totality of bits of data flowing about, whatever may be their bureaucratic origin and whatever may be the organizational entity that collects, processes and acts upon it. It's one of the features of the year 1976 that many of these departments are coming out of the woodwork and a lot of us are involved in trying to glue together what has become a very splintered arrangement. That's an extra added burden on the current situation. That's a very serious problem. There are many serious men fighting it and there are many lobbyists involved in it.

REMARKS OF THE WORKSHOP

by LT. GENERAL W. L. CREECH
Hanscom Air Force Base

It is important to assess our current situation with regard to Tactical C^2. We need to see what we are doing right and what we need to improve. First, we need a common frame of reference for Decision Information and Tactical Command, control and communications. There are four fundamental questions that describe an engagement:

1. With whom will we fight?
2. Where will we fight?
3. On what scale will we fight?
4. On what timetable will we fight?

The development of an appropriate investment strategy is not an easy task. The influence of Congress makes a long range strategy difficult to maintain. The limitations of money lead to certain tradeoffs. One tradeoff is that of quality versus quantity. Another is that of one program over another.

I believe that we are generally doing a good job currently. Nonetheless, it is instructive to consider our liabilities.

First we should consider some of the possible situations that could arise. We can handle any situation in the third world except perhaps PRC. Another possibility is a conventional war with the USSR in central Europe. There are other areas where it is unclear whether we would fight and on what scale. One would probably fight to defend the oil fields of the Middle East and Japan, and less likely, to defend India, Korea or Formosa.

There are several generalizations that we must consider. The USSR has the advantage of knowing where they will fight. They probably would fight in central Europe but not in Chile. There are some areas where the U.S. must rely on nuclear weapons, both tactical and strategic. All these complexities must be considered in planning tactical C^2. We must not rely on abstrac-

tions. We now examine some of the areas that may require adjustments in our investment strategy.

One such area is central Europe. A major problem is insufficient communication. This communication must be in both directions, up as well as down the line of command. The problem lies in the basic infrastructure in the locations where we are most likely to fight. This difficulty supercedes even the problem of what to communicate. One part of the reason for this lies in NATO expenditures. Improvement in this area is made more difficult by the complexities of decision making.

Another area is Soviet electronic warfare. They have the ability to cut off the flow of our decision making information. If they can destroy 30% of our communication and disrupt another 30%, they can totally destroy our ability to communicate effectively. We need really dependable UHF radio and digital encoding. Currently we have placed too much emphasis on security. We need more emphasis on jamming and other offensive electronic warfare and less on defensive measures. The USSR is in a good position in Central Europe but they are vulnerable. This vulnerability stems from the tight control they need to maintain over their middle management.

The area of intelligence handling, processing and dissemination is another that needs improvement. Here, a major key is dissemination of information downward. A good example of this is ITITS (Intra Theater Image Transmission System) used to control T-39's in Southeast Asia. But the problem remains of exploiting the current system to get information down to the lower levels. A complication here is the problem of information overload and the problem of quantity versus quantity. We need to cut the time lag on this information as well as to deal more in aggregate information.

We should also consider the problem of enemy identification, the electronic sorting of Friend from Foe (FFF). This is needed to allow the use of electronic fire systems. This would include

the air traffic control system which currently is too cumbersome. Another difficulty in the current system is that it identifies the friend and treats all others as foe.

The last area of concern is the problem of deployability and survivability versus sophistication. Current technology tends toward sophistication and against reliability. Automation is often needed but reliability should not give way totally to sophistication.

Currently we are experiencing a trend toward overcontrol that may prove counter-productive. The main point here is that we should not generalize too hastily. The Mayaguez incident benefited from real time control from the Pentagon. However, we cannot extrapolate from this to all other situations. In Southeast Asia, we had our own timetable. We were not under attack. This lead to control from the White House. On the other hand, in the action at Entebbe, the Israeli chief of staff only listened in to ground communication. They had learned the hard way to stay out of such decisions.

Before closing, I would like to consider some positive notes - the things we are doing right. The use of airborne radar can change C^3. We now have the ability to deliver aggregate information. It also reduces the need for other information being sent to command. We are making gains in interoperability and information exchange between the services. However, we tend to overlook interoperability with our allies. We have also been successful with our links between research and application.

C^3 AT SEA: A COMMANDER'S VIEW

ADM. GEORGE E. R. KINNEAR, II

When you set out to design a system you usually have some specific purpose in mind. Quite often what you start out to do can change due to a number of things. You have the problem of technological innovation happening so rapidly that somewhere along the line you have to get tough and freeze the design and quit thinking in terms of what you might do and go on and do something. The design may not be perfect or may not do all the things that you set out to do but at least you have a "system." I think that researchers are somewhat free about this but certainly our applications specialists have to think carefully about it.

As an example of that, I know of a real live case where this little old lady lost her husband and became very lonely. She had a very astute systems engineer son who took charge of the situation and said that what you need is companionship. We will get you a kitten. Now if you stop the design problem there everything is o.k. because she brings the kitten in and it is very lovable and a sweet kitten. Everything worked great. But circumstances changed just as sure as they change in other parts of the real world and that kitten became a cat. It turned out to be a male kitten. Then it became a Tom cat. Tom cats have certain characteristics that are well recognized if you realize ahead of time that that kitten is going to become a tom cat. This case was typical. Every night he went out carousing around and then, dragged himself back in the morning, often in disarray, physically abused, always tired and hungry. Instead of having that cat as a companion as she set out to do, the lady had a cat she had to repair, feed and watch sleep all day.

She went back to the systems engineer son and said that it was great when he was a kitten but it is not that way anymore. Well, the son said, "that is easy to fix. All you have to do is the right kind of engineering and we can return him to his ori-

ginal state. We'll take him down to the veterinarian and we'll get him fixed." So she thought that that was a pretty good idea and they did.

Then they brought old Tom home. He hit the kitchen floor, looked around, went over and curled up by the fireplace and went to sleep. She thought, he doesn't realize that things have changed and he will be better tomorrow. Well, come sundown, Tom went and scratched on the back door. The lady thought about it for a while and then decided to let him out. Tom went out and bounced up on the back fence. He was up there with several of his old buddies when one of the more management-minded of the tom cats said, "Tom (after being told what had happened to him) "you know what they old lady has done to you"? Tom said, "well, yes, I guess I do." His buddy said, "Tom do you realize the full implications of this?" Tom said, "well, what is the bottom line on that?" "Well, Tom, the bottom line on that is that you have got to make up your mind whether you are going to be a teacher or consultant."

I am a naval officer primarily - and don't ask what is a nice guy like me doing in a job like legislative affairs, because that story is too terrible for the ordinary citizen to hear. Basically, I am an engineer at heart, but certainly if I am anything, I am a naval officer. Naval officers are in the business of producing combat capability at sea, for purposes of controlling the seas. We have a mixed bag of people here. Accordingly, let me make a flat statement. I don't intend to excite you. I just intend to generate a little interest on your part, and say that unless we plan on going to war with Mexico or Canada, there is not going to be a next war unless we have control of the seas. The Air Force will not be able to function without its jet fuel and the other kinds of things necessary for air warfare that must come by sea. The Army for the same reason would not last very long without supplies and equipment carried by sea. So I take my business of seapower very seriously.

Not to have command of the seas - and you would assume that we have the forces necessary to maintain control of the seas - involves the solution of a number of problems. Let me illustrate this for you with a current example. A few years ago I went to sea as a commander of a carrier group. My first introduction to where we were both in C^2 and C^3 at sea in a tactical situation came in the following form: I was sitting on the flag bridge of the U.S.S. Kitty Hawk near Singapore looking at a couple of my ships that were working a very simple problem. We were trying to move to the South China Sea without any aircraft coming out of Guam being able to identify which radar blip was the carrier, something we practice all the time. There are all kinds of ways of fooling aircraft that are looking for carriers at sea. The first time that we have to communicate they have us, just about, unless we are playing the game. We had no destroyers in company with us. We had detached them for individual ship exercises over the horizon about 20 miles away. We were using helicopters for plane guard and were conducting flight operations at that time. Kitty Hawk was the first multipurpose carrier in the Pacific environment. She had a pretty neat mission. Everybody for whom I worked made very clear what my goal was.

We had a replenishment group with one of our newer replenishment ships at the center of the formation about 40 miles back. They were on a slightly different course in order to keep the wind and sea in the right position for an easy replenishment at sea. Things were going very neatly. Sunday morning, light winds, nice sea state and I was for the first time feeling the full glory of command at sea. I got a garbled radio message that said words to the effect "...this is the replenishment group... we have a submarine back here with us." Well, that did not sound too serious, except that we did not have a submarine that was supposed to be a part if the exercise.

I had a very well qualified staff and being the new boy on the block I did what any reasonable commander would do. I

thought to myself, "Okay, this is a wonder time for me to keep my mouth shut and watch my staff go into action." The first thing they did not try to go to other sources and find out if there was a submarine that we are aware of in this general area. That is the sort of stock first step in that sort of situation. The second thing they did was say, "let's break off the exercise with the aircraft that's coming down to look for us, go into our ASW mode and cancel our exercise."

That was a little distressing to me because I have the feeling that if we go to war with the Russians they are not going to let us fight the war in phases. We'll not be able to do ASW part of the time and anti-air part of the time and then get around to the anti-surface later. We have to be able to do all at the same time. I became somewhat disquieted.

We had an airborne early warning aircraft up, so I suggested "Why don't we move him back, use him as a communications relay, keep the air exercise going and see if we can't approach this as a single problem. It turned out that it was not a submarine that they had reported. It was a periscope. Until we could verify the information we had on the submarine, I decided to keep working the air problem. "In the meantime, I said, "why don't you call the destroyers that are on individual ship exercises over the horizon and head them back that way."

Well that sounded simple until I found out that we could not raise them. We were trying to stay off HF because of the air problem, knowing that if we came up on HF that aircraft would have a fix on ut. We could not communicate with our own destroyers, although they were less than 20 miles away, and get them headed toward the ASW contact. It was very interesting, because by some freak we were able to communicate with the replenishment group twice as far away in a slightly different direction.

I won't belabor you with the whole thing, but I suddenly became aware that there were a number of problems that had not been solved since the last time I had been at sea. One of them

was tactical communications at sea. That is not really the main thrust of what you are doing here, but I will come back to it because it is central to everything that we have to do with respect to command and control. You can build all the management information systems that you want, but if you don't have the ability to implement your decisions, to know how your implementing actions are going and to get feedback, you are in serious trouble. You can forego a communications system up to the time of making the decision but decisions are useless if you have an inadequate tactical communications system. So you cannot neglect the third C of communications although I know the purpose that you are down here forprimarily you are interested in the first two.

I will put on my professorial mode now and tell you that most commanders at sea have a mission, that they are well aware of. Perhaps I am telling you that I should have been the first lecturer this morning after hearing the sophistication of the previous one. You may be relieved to know that I am going to comment on a real grassroots level situation as a simple-minded commander at sea with problems and in need of some help.

Within our mission we have specified tasks. Certainly the capable commander will have defined the priority of the tasks within his mission even if higher command has not. He will make these priorities abundantly clear to his subordinates. If he doesn't, he has lost "at bat" even before he starts.

In addition to knowing his mission and tasks, and having everything ordered in priority, he must also have full appreciation of the resources he had available to him. Those resources can come in many forms. They can be basic weapons systems, black boxes, the people who make them go, all forms of support, everything under the sun that can in any way contribute to the accomplishment of your mission at sea. Then, of course, the other thing that he has to have a good knowledge of and he has to have a full appreciation of, is his staff.

There are three basic things that are threaded through this. One of them is data. One of them is information. And one of them is decision. You say, that is so simple, why do you even bother to beat us over the head. Well, let me tell you that I have a great problem communicating in my own community. I don't know if you have this problem or not, but the simple distinction between what is data and what is information is difficult in my community. I have a very simple, straightforward theory about organizations and I have got one about the difference between data and information. Let me tell you this theory about information and organizations. You have probably been exposed to both already today. There is no organization in the world, no matter how cleverly and how well designed it is, that can't be screwed up if you get the wrong bunch of human beings in there trying to make it go unless it is going to be a system that does not require human participation (and it is hard to find one). It does not make any difference how well the engineer, systems designer or anybody else does their work. You get the wrong bunch of people in there and they can screw it up. By the same token you can take the worst designed system - at least theoretically worst designed system - and if you give me the right collection of people, I will make it work for you. I don't care how bad it is. It may not be a perfect performance, but I can make the darn thing work for you. I guess the point is that quite apart from the hardware, from the design, from all of the thinking that goes into putting a system together, you can never neglect the human element. It is going to be in there and you have to design that system for the least capable human being that is going to try to use it. If you don't believe that, I can give you a lot of examples.

Now, to the difference between data and information. I don't want to belabor this point. This was a good point that Dr. Miller made as he went through the hierarchy of sophistication. What is information at one level may be data at another level. The point

is that the raw data itself is very seldom useful in decision making. It has to be processed in some way. What turns out to be information at one level in a form perfectly adequate for what has to be done at that level has to be processed again to be suitable at a higher level of sophistication. He mentioned this very specifically, this compression factor that you keep refining as it goes upstream. As it comes down from the top, of course, it has to work in the opposite manner. Think about that, and keep it in mind anytime you build a system that is going to be used for the purposes of command and control.

The only reason that you have for gathering data, processing it, creating information, refining it, and driving it upstream in any system is that, ultimately, it is going to contribute to making a decision. Then there is the other important aspect. Decisions having been made are useless, in general, unless they are implemented. You have the other side of the process to come down, so to speak.

If I talk in terms like that, you say "Well, all he is talking about is "MIS". He says, "Design me a management information system." That is all he really wants. By golly, you're right. You can make the case that the only thing I need to be effective in command at sea is a pretty good management information system. Now what would I need in that? Again, I have given you a very basic approach to this thing, but these are the things that I would have to consider before I made any kind of tactical decision. I would have to know what I have in the way of my own forces. Well that is easy, I count them. You have a list of them. It is easy to know how many ships and airplanes you have, their capabilities and that kind of thing. But there are some other things to consider and you might note that you can define two general catagories of information. You have static information. The kind of stuff that you know that you could put into a data base. It changes very slowly, if at all, and quite often it is an "in or out" kind of thing. Either a

ship is afloat or it is sunk. You know that. Then you also have dynamic information which gives you something beyond that. It changes very rapidly. You can make the distinctions between those two categories very easily.

Somewhere in the fast moving tactical situation you have to start taking into account intent. But that puts you into a probabilistic situation, and the information I am talking about is much more certain than that. The guy either has the capability or he doesn't. Either he has a missile system or he doesn't have a missile system. If he has a missile system, either it is working or it isn't. The last thing is if that missile system is working, has he any missiles left to shoot? That is more of the dynamic information. So, if you have an ideal management information system for tactical decisions, you would have some neat things in there. Pretty easy to get these on your own task force as to not only what you have with you and what your capabilities are, but also where they are. That is a tough problem.

Let me make a point here because there is a variety of people here with different backgrounds. That is that the toughest problem that you would have would be the air warfare problem, as regards tactical decision and command control. The easiest problem we should have would be the one at sea. I would like to tell you the Navy has it solved but I am sure that you have discerned about now that I don't think we have. Actually the one that should be the most manageable - and if you take a look at the requirements for management information systems you can see why - would be the one at sea where you have a relatively simple sterile environment. A lot of things in the air battle situation happen very rapidly but in general the things that happen on the surface and the subsurface part happen at relatively slow speeds - and you don't have the casual intruder. Even in air warfare, you can have a casual intruder. Most people like to stay away from

fighter pilots who have loaded missiles and that sort of stuff, whether he is flying another airliner or fighter. It is even more manageable under sea conditions. I would like to think that if you are going to look at a basic problem, that you would think of the sea problem because that is pretty manageable compared to some other things. I suppose there are probably smiling commanders here that are amazed to hear me say that I think their problem is tougher than mine - there are too many variables in land warfare that I don't have to deal with.

What I want to know in a real or potential combat environment is the disposition of my own forces, what kind of condition they are in, - in other words the capabilities that are built into each individual ship, each individual airplane, and how many will operate. How many missiles do they have left? How many rounds of ammunition? You must know, if you are in battle, the present condition of the units and pproblems that are not just a matter of every day maintenance -- not just the sort of thing that you are normally reporting, but special battle reporting to tell you how you are foing from the standpoint of material condition, capabilities, casualties, equipment and expendables.

If that is what you want to know about your own forces, what about the threat forces? Pretty obviously, you want to know the same thing. You want to know the composition of the threat forces, and you want to know their capabilities. Static and basic. On the dynamic side, you want to know the where and when. Where are they and when were they there and that sort of thing. The older the when, the less certainty there is about the where. You people who like to deal with probability can take a look at that problem and help us solve it, particularly when it comes to building decision-making models.

If you have that kind of information, where do you get it and how do you use it. One of the things that I found out on Kitty Hawk was that I did not have the ability to handle the volume of information generated by my own forces. How do naval

forces at sea generate information? Well, they collect a lot of data and they process it in different ways. What are the data collectors, what are the information collectors, depend on how you want to look at it. What are the general categorizations that you can assign these collectiors. Passive and active. Which is better? Man, give me the passive one every time. The active information gatherer like a radar gives you real fine information, is very useful, but you give that other guy an awful lot of information in return. Sonar is the same way. I prefer sonar to active sonar. The information you gather is much more valuable to you if your enemy, real or potential, doesn't know that you have gathered it.

Let me at the same time say this about com munications systems. Think how wonderful it would be if we had communication systems that met all the requirements in terms of speed and reliability and security, and yet were passive. Just think of having the ability to communicate without the enemy knowing that you are communicating. Right now we can keep them from understanding what we are communicationg, - but they know that we are communicating in just about every system that we use.

We have got all of this data, all this information and we can build a tremendous data base and we can inundate ourselves with the information generated at the local level alone. In today's world this is just not enough. The ability of the enemy to launch long range missiles from submerged submarines surface ships, and backfire bombers, or other air platforms, makes a situation where you simply cannot be concerned solely with the information that you generate locally. You may be making a lot of quick, short term decisions based on what you generate locally, but if you are going to survive, you have to know what is happening over the horizon and beyond radar range. You simply do not have the time with the weapons systems that we have now, and that we will have in the future, th survive a saturation attack at sea unless you have some prewarning of what

is coming and where it is coming from. That means that you probably will be tied in to other sources of information that are exterior to your own task group, whether those sources are other naval forces at sea, satellites, or whether they are other central systems owned by other agencies of the government. It makes no difference from where it comes. You still must have a way of tapping that kind of system if we really get serious about war at sea.

If you have all that information dumped into the data base, obviously, you must have some way to use it. You have gathered it, you have stored it, now you must have some way of sorting it, being able to call it in a form and a time, and in a fashion that helps you make orderly decisions. Here, the software people come into their own. They can once again saturate you. There are numbers of ways that you can sort that information, depending on how you have built your data base. Let's say we have had an intelligent design, and that you have an almost unlimited number of ways that you can call that information. In the case of ECM or electronic signatures, it can be by frequency, it can be by pulse repetition rate, or any of the parameters that can go to describe the electronic signal. You can sort by them. You can see that the combinations available are almost unlimited.

Having done that, you need some way of presenting that to the decision maker. If you stop to think about the number of ways you can present information, right off the bat you have CRT's, you have teletype, you have voice. It can be a large screen display. There is a whole family of those, whether you use liquid crystals or light values. There are almost unlimited combinations there of how you can display information. When you get down to that point where you are going to display information, you are doing it for a purpose, and that is to make a decision. I think we are finally at a point where you applications people can address a real problem. You could come up with some good software programs that will assist the decision maker by letting

him, before hand, build some decision models. We could build models that have provisions for stochastic processes. Those stochastic models certainly would not be infallible, but they certainly would be an aid to the tactical decision maker. Specific applications such as taking electronic signatures and the sequence in which those signatures appear, and the direction and the speeds of the emitters and that sort of thing, you can come up with some pretty solid patterns as to what the enemy is doing. One of the problems that you always have is the possibility that you are being spoofed. So you are going to have to build some sort of check system to discriminate between the spoof signal and what is probably a real signal. Certainly there is almost unlimited opportunity to take a look at all the information that is being put into that data base, select out of these certain things that satisfy the requirements of your decision model, and display that is such a way that the decision maker will have an additional aid.

The big fear of everybody when you talk about this is they are going to ask the commander to give up his own intellect and depend on a computer to make a decision for him. Not so, at least in my estimation. It is an aid to the decision-maker. Nothing more, nothing less. There is atremendous amount of research that has already been done in this area. There are some great models already working. There are some terribly smart people that are pursuing R & D in this area. I can think of norhting more challenging to use, and more useful to me, then to be able to come up with those kinds of decision models and tie them into a computerized tactical command center at sea.

The last part of this process comes after having made a decision. Sometimes the decision is not to do anything, but in a combat situation usually the decision is to get out and do something. It is an aggressive action done in a timely fashion. The system that you built has to be able to track the implementation of your decision and provide you the feedback necessary

for the next generation of decision. Let me say that anybody who is going into combat would like to know he has a 99% probability of winning. You can find yourself in a situation where you lose a battle and it is not a mistake in the system. The tactical commander did not do anything wrong. He simply was in a situation where he was destined to lose. Somebody else may have made a mistake, but it certainly was not even at the theatre level. It may have been a coincidence, such as a typhoon that kept him from employing the forces he had available. I don't like to think in terms of mistakes. I like to think of relooking at the situation as it exists at a given time and to decide what will happen next. It doesn't matter whether it was a mistake, or on purpose, or an act of God, or whatever. The data base should be absolutely insensitve as to motivation and how you got like you are. It does have to be a system that is sensitive to decision implementation and takes care of that last bit of feeding back to the total system so that the decision maker is in a dynamic process at the time.

I have already mentioned the fact that the key to this, and also I might add, the key to gathering data, passing information and implementing decisions and getting feedback is to have a communications system. I don't know how the rest of you are doing but with what I had to operate at sea and what I see going aboard our ships the Navy is not impressive in this area. I might enjoy getting in the last word here by saying don't believe those that say satellites will solve all of this. If you want to hear my caustic comments on satellites, I was in an operational exercise, Nickel Plate, when I was out in WEST PAC, and I saw operational immediate messages coming in 24 hours after they were issued. The system became hopelessly strangled. It may have looked great back at the Pentagon but at the other end it did not look so good. Admiral Steele, who was the commander of the 7th fleet at the time, came over and he said, "they tell me that this will be corrected and that we won't have to depend on HF communi-

cations. We will have the satellites and we will go all SHF, UHF, whatever. We won't have all the problems any longer. But that worries me a little bit, because the first thing when the balloon goes up, the satellites are going to come down." I thought about that for a while and after watching up operate out there I said, "If the Russians really know what they are doing, they will leave the satellites up."

I had not intended to stagger your imagination. I have intended to stimulate what you might have considered an opportunity to pick the brain of a guy who has been pretty frustrated in his own personal attempts to solve the kinds of problems that we are talking about. I did come up with something called Outlaw Hawk, thanks to Julian Lake. Lots of hard work by Nell Nauglex and my staff. We put together a computerized tactical command center on board the Kitty Hawk using "off-the-shelf hardware." We gained an awful lot of knowledge as far as demonstrating different concepts. We did not establish how the Navy should to in solving the TFCC Problem, which is only part of the overall C^3 problem. We did establish that a computerized system is necessary to optimize on which our existing hardware systems can do, and that software is the real challenge in respect to how to go. It was also demonstrated that communications, both internal and external, are probably the limiting element of C^3 in todays combat environment.

DISCUSSION

Dockery: I have been making an observation about your decision models. It seems like what you are really talking about there is a software package of real time information about which only a sort of trip wire decision is made; for which only some sort of very simple algorithm exists which says that if it is above some threshold, display it. I think this is the step between there and something like that, but it would make a distinction. I think you are talking about a package, is that correct? Something that packages their real time information.

Kinnear: Well, you are getting into deep water - what do you mean by real time information?

Dockery: I think the radar sensor data - the flowing in of relatively indigested information, pieces of equipment, or people who press a button that enter some type of data produced, as opposed to really evaluated information.

Kinnear: O.K., it depends on the level of the decision you are planning on making. Of course the thing we have now in lieu of that in view of the fact that we have the human intellect, is the staff. That's the only thing that kept me alive -- the fact that I had a well qualified staff when we got into a tough situation. Incidentally, two conditions usually existed. One, you didn't have enough information to make an intelligent decision, and secondly, you had more unevaluated information which had not been properly put together than you could handle and, and a result of which, you got saturated. There never seemed to be an in-between. Of course, the way to cut through the last one is to have a very knowledgeable set of software walking around on two feet you help you with that problem. Of course, they are preprogrammed in a lot of different ways and if you have been smart about the kind of people you have on your staff, hopefully you will have a mutually supporting group of software programs there that can get you around the problem you are talking about. As for what I am

talking about ultimately downstream, the alternative suggestions, that is one thing that would have to be an output. It would have to give you an evaluation and then a recommendation of some sort. But as to how high you can drive that thing through a computer, I am a little uncertain right now. Unfortunately, something you are going to find out when you get into this thing, is that what is considered to be optimum by the operator is going to be a functional by the individual and the people that he is working with. How much help does he want from it? I didn't answer your question. It appears that in order to be a real decision maker, it has to be a model to a certain degree of both yourself and your staff. It has to be able on the basis of the information available to generate, say, the four or five most common alternatives one of which you will accept when presented or, if you reject them will generate new ones. The step between that and the sort of simple processing you are talking about is a rather critical one.

Modrick: "One way to look at the computer aided command center and decision aiding is that it's necessary because the staff is overburdened with the information processing that they originally did. There are several ways I can ask the question, one is: if you go to the computerized operation, are you willing to give up the staff that it is replacing or to put it pejoratively, is this a sneaky wah to increase manning by buying computers instead of people?"

Kinnear: It's a trade off in my estimation. I will give you a personal answer on that. I would never think of getting rid of my staff for a number of reasons. You may be able to reduce the size of your staff if, in fact, the only reason they are there is to help you make decisions. But, of course, as we realize, the control of the data base and the kinds of things that go into that and the ability to get meaningful things from a data base is usually, at least with the kinds of situations I am familiar with, very dependent on the kind of people you have on the staff. So they have got two functions: one, they aid you in decision

making. The other thing is that they are really the people who are writing the orders and determining the design of your data base in a dynamic fashion as far as what you are putting in there, and have the ability to put the right kinds of things in there. Lord knows there is not a computer in the world big enough to store everything you might want to know, so you have to be selective. The other thing is correlating the information you have got in there. You can build a routine that will do a great job in assisting you in correlation, but one thing we found out in Outlaw Hawk is that while a computer can be a great assistance in that, the best system you have got in correlation between very diverse bits of information is the human brain. On a particular target we had 35 elements in there, information elements, if you will, and if we can determine 15 of them I can essentially give you the names of the platforms or the bureau numbers of the airplaine - only 15 of that 35 can do that. The computer is pretty stupid. It can really handle a lot of stuff - but as far as its ability to pull things together and make a determination as to what that platform was, and correlate the different kinds of information - electronic signature with the acoustic signature with other kinds of information you might have, - that process still required the human being. I think what might happen is that if you build me decision models that would hekp me in my tactical decision making, I would still want to keep my staff. I would still know that, as far as managing a data base, particularly in the correlation function, I would have a different kind of staff, but it would still be there.

Question: "I was interested that you started off saying you knew what you wanted to do when you went to sea. You had a pretty good idea - you stated your mission, you had your task. That's sort of standard, everybody carries that around with them. One of the things we had difficulty in trying to evaluate what you were doing in Outlaw Hawk was in deciding what your mission was, what you were really trying to do. Navy officers carry that

around very nicely themselves and keep it well undisclosed, because I was watching them in operation. I think that might be the source of a great deal of difficulty in trying to create facilities like TSC and Outlaw Hawk and other such things, because you don't agree among yourselves, because you don't let each other know what you are thinking. It is just a suggestion or a challenge, you might say.

Kinnear: No, it is probably a legitimate comment. It doesn't particularly fit me of course, but as much as you were there, you have every right to make it. The thing that doesn't go along with Outlaw Hawk, of course, is the operational order. I don't believe it went along with what we were supposed to be doing on the many different phases of that particular operation. We proceeded about ten days in that. Of course, even after you finished, there was some uncertainty as to what it is we thought we were doing. That's sort of like being in Washington. You stop any number of people in the Pentagon and ask them what the mission of the Department of Defense is and you will get as many different answers as you do people. If you like the one about the ant floating down the river on a log. As long as it is going downstream you could ask any ant on there and he would tell you that he was steering, but you let the damn thing turn around and each one will turn to the other and "but I though you had the conn". It is somewhat that way in large operations at sea. However, the Third Fleet OP-ORDER and the OP-ORDER that took the 30 ships to sea snd set that thing into motion we had pretty well defined, and there were specific tasks in there.

Question : I didn't mean it in that kind of global sense, but when it came time to make the decision you were going to make. If you were going to have someone build programs and assist you in making decisions, it is not at all clear which ones are most important to you. It is very difficult to get from you which is the most important. The same thing came up earlier before you arrived, when General Creech was talking about proposals. He

said the arguments it took to get a $12 million ORFINC facility established in Central Europe were more difficult than getting the $1.5 billion dollar aircraft program off the ground. I think our experience with TFCC has been every bit as prolonged, and we have as yet to succeed. I am interested in how, after a year and a half, since your playing it from the other end, how do you convince your own community that 12 million dollars isn't all that much money?

Kinnear: I didn't, I am still being criticized for the project. It's lack of appreciation that it was only intended to demonstrate concept, and not to establish a hardware suit and that sort of thing. I think that the real valid point that you made there is that the importance of decisions is rather situational. I don't think you will ever be able to come up with a real hierarchy as to which decision is more important. There is one thing that you can always hang up about combat. You were talking about what motivates people and the military comment said that if you hang a ribbon or a medal, or a little bit more pay, out in front of a guy, you can get so much motivation. Maybe you could appeal to his ego. That's great, but the bottom line of contact is that you would like to come out of it without swimming if you are in the Navy and, of course, if you are in an airplane you would like to end up going home in the same airplane you went out in. Basic motivation -- bottom line motivation -- is to keep butt and soul together. That's situational too tough. Of course, different kinds of motivation will drive different kinds of people in different kinds of situations. The hierarchy of decision making, and the kinds of models you build, I don't think will every be very constant because they are very situational. Like I said, I am not smart enough to know how to put that together, but I would like to think that, with the gathered talent we have got in this room, there is bound to be some real gain that can be made. I have not been impressed, however, with the progress we have made in this particular area. That's just a fact of life. If I am

wrong, convince me of it and I will apologize. Otherwise, you have to buy me a beer.

Question: "How can we get the operation to better articulate as to what sort of information makes a difference in their decision process? Too many of these systems, for lack of that articulation, we collect everything we can and try to process it. The result is somewhat of a random process of supporting the Commander.

Kinnear: Well, I can't give you a very satisfactory answer. The only thing that I can say is that building the most flexible system that you can, so that I can make it react to the humans I have involved in the decision making process and adaptable to the circumstances under which the decisions are going to be made. It will have to an interactive data base, and there are a lot of parameters I can give you on a data base. But I can't give you any pat answer to the question you ask, because we are dealing with things that have to do with circumstances and human beings. I can't control either one of those. It would certainly make your job easier. The only thing I can say to you is that you will have to build one that is flexible enough that it can be used with any gathering of decision makers who may be given the opportunity or forced to use that system. It is going to have to satisfy every possible circumstance under which those decisions might be made. That is a big order. I recognize it, but I can't diminish it because that is just the way it is."

II. TECHNICAL PAPERS

Dr. Miller's talk was based on a chapter in his forthcoming book, Living Systems, McGraw-Hill, 1977. This chapter appeared under the title, "The Nature of Living Systems," in Behavioral Science, Vol. 21, 1976, pp. 295-319. We give here three tables from another of his papers ["Second Annual Ludwig von Bertalanffy Memorial," Behavioral Science, Vol. 21, 1976, pp. 219-277] which may help the reader to follow the discussion on the talk.

TABLE 1

THE CRITICAL SUBSYSTEMS

Subsystems Which Process Both Matter-Energy and Information	
1. *Reproducer*, the subsystem which is capable of giving rise to other systems similar to the one it is in.	
2. *Boundary*, the subsystem at the perimeter of a system that holds together the components which make up the system, protects them from environmental stresses, and excludes or permits entry to various sorts of matter-energy and information.	
Matter-Energy Processing Subsystems	*Information Processing Subsystems*
3. *Ingestor*, the subsystem which brings matter-energy across the system boundary from the environment.	11. *Input Transducer*, the sensory subsystem which brings markers bearing information into the system, changing them to other matter-energy forms suitable for transmission within it.
	12. *Internal transducer*, the sensory subsystem which receives, from subsystems or components within the system, markers bearing information about significant alterations in those subsystems or components, changing them to other matter-energy forms of a sort which can be transmitted within it.
4. *Distributor*, the subsystem which carries inputs from outside the system or outputs from its subsystems around the system to each component.	13. *Channel and net*, the subsystem composed of a single route in physical space, or multiple interconnected routes, by which markers bearing information are transmitted to all parts of the system.
5. *Converter*, the subsystem which changes certain inputs to the system into forms more useful for the special processes of that particular system.	14. *Decoder*, the subsystem which alters the code of information input to it through the input transducer or internal transducer into a "private" code that can be used internally by the system.
6. *Producer*, the subsystem which forms stable associations that endure for significant periods among matter-energy inputs to the system or outputs from its converter, the materials synthesized being for growth, damage repair, or replacement of components of the system, or for providing energy for moving or constituting the system's outputs of products or information markers to its suprasystem.	15. *Associator*, the subsystem which carries out the first stage of the learning process, forming enduring associations among items of information in the system.
7. *Matter-energy storage*, the subsystem which retains in the system, for different periods of time, deposits of various sorts of matter-energy.	16. *Memory*, the subsystem which carries out the second stage of the learning process, storing various sorts of information in the system for different periods of time.
Matter-Energy Processing Subsystems	*Information Processing Subsystems*
	17. *Decider*, the executive subsystem which receives information inputs from all other subsystems and transmits to them information outputs that control the entire system.
	18. *Encoder*, the subsystem which alters the code of information input to it from other information processing subsystems, from a "private" code used internally by the system into a "public" code which can be interpreted by other systems in its environment.
8. *Extruder*, the subsystem which transmits matter-energy out of the system in the forms of products or wastes. 9. *Motor*, the subsystem which moves the system or parts of it in relation to part or all of its environment or moves components of its environment in relation to each other.	19. *Output transducer*, the subsystem which puts out markers bearing information from the system, changing markers within the system into other matter-energy forms which can be transmitted over channels in the system's environment.
10. *Supporter*, the subsystem which maintains the proper spatial relationships among components of the system, so that they can interact without weighting each other down or crowding each other.	

TABLE 2

Selected Major Components of Each of 19 Critical Subsystems at Each of Seven Levels of Living Systems. The Components of Seven Subsystems, Identified by *, Are as Yet Unknown

Subsystem	Level						
	Cell	Organ	Organism	Group	Organization	Society	Supranational System
3.1.1 Reproducer (Re)	chromosome	none; downwardly dispersed to cell level	genitalia	mating dyad	group that produces a charter for an organization	constitutional convention	supranational system which creates another supranational system
3.1.2 Boundary (Bo)	cell membrane	capsule of viscus	skin	sergeant-at-arms	guard of an organization's property	organization of border guards	supranational organization of border guards
3.2.1 Ingester (IN)	gap in cell membrane	input artery of organ	mouth	refreshment chairman	receiving department	import company	supranational system component that admits new members
3.2.2 Distributor (DI)	endoplasmic reticulum	blood vessels of organ	vascular system	mother who passes out food to family	driver	transportation company	UNICEF, which distributes food to needy children
3.2.3 Converter (CO)	enzyme in mitochondrion	parenchymel cell	upper gastrointestinal tract	butcher	oil refinery operating group	oil refinery	EURATOM, concerned with conversion of atomic energy
3.2.4 Producer (PR)	enzyme in mitochondrion	parenchymel cell	unknown*	cook	factory production unit	factory	World Health Organization (WHO)
3.2.5 Matter-Energy Storage (MS)	adenosine triphosphate (ATP)	intercellular fluid	fatty tissues	family member who stores food	stock room operating group	warehouse company	International Red Cross, which stores materials for disaster relief
3.2.6 Extruder (EX)	gap in cell membrane	output vein of organ	urethra	cleaning woman	delivery department	export company	component of IAEA concerned with waste extrusion
3.2.7 Motor (MO)	microtubule	muscle tissue of organ	muscle of legs	none; laterally dispersed to all members of group who move jointly	crew of machine that moves organization personnel	trucking company	transport component of NATO
3.2.8 Supporter (SU)	microtubule	stroma	skeleton	person who physically supports others in group	building	public building and land	United Nations building and land
3.3.1 Input Transducer (it)	specialized receptor site of cell membrane	receptor cell of sense organ	exteroceptive sense organ	lookout	telephone operator group	foreign news service	news service that brings information into supranational system
3.3.2 Internal Transducer (in)	repressor molecule	specialized cell of sinoatrial node of heart	receptor cell that responds to changes in blood states	group member who reports group states to decider	inspection unit	public opinion polling agency	supranational inspection organization
3.3.3 Channel and Net (cn)	cell membrane	nerve net of organ	neural network	group member who communicates to other members	private telephone exchange	national telephone network	Universal Postal Union
3.3.4 Decoder (dc)	molecular binding site	receptor or second-echelon cell of sense organ	cell in sensory nuclei	interpreter	foregin language translation group	language translation unit	supranational language translation unit
3.3.5 Associator (as)	unknown*	unknown*	unknown*	none; laterally dispersed to member who associates for group	none; downwardly dispersed to individual persons, organism level	teaching institution	supranational scientific organization

TABLE 2—*continued*

SUBSYSTEM	LEVEL						
	Cell	Organ	Organism	Group	Organization	Society	Supranational System
3.3.6 Memory (me)	unknown*	unknown*	unknown*	adult in a family	filing department	library	United Nations library
3.3.7 Decider (de)	*regulator gene*	sympathetic fiber of sinoatrial node of heart	part of cerebral cortex	father of a family	executive office	government	Council of the European Economic Community
3.3.8 Encoder (en)	component producing hormone	presynaptic region of output neuron of organ	temporoparietal area of dominant hemisphere of human brain	person who composes a group statement	speech writing department	press secretary	United Nations Office of Public Information
3.3.9 Output Transducer (ot)	presynaptic membrane	presynaptic region of output neuron of organ	larynx	spokesman	public relations department	office of national spokesman	spokesman of the office of Warsaw Treaty Organization

TABLE 3

CHANNEL AND NET SUBSYSTEM AT THE LEVEL OF THE ORGANISM, ITS VARIABLES AND INDICATORS

Variables All Levels (Channel and Net Subsystem)	INDICATORS Organism Level (Channel and Net Subsystem, Neural Components)
Meaning of information channeled to various parts of the system	Measure of the change of the signals transmitted over a neural tract on the processes of the organism
Sorts of information channeled to various parts of the system	Frequency range or source of information of transducer which inputs signal into a neural tract
Percentage of information arriving at the appropriate receiver in the channel and net	Percentage of total number of bits input to a neural tract that are output from it in a specific period
Threshold of the channel and net	Intensity of output from another information processing subsystem required to input a signal over a neural tract
Changes in channel and net processing over time	Differences in meaning, sort, rate, distortion, or other aspects of signal trasnmitted over a neural tract between one time and another
Changes in channel and net processing with different *circumstances*	Differences in meaning, sort, rate, distortion, or other aspects of signal transmitted over a neural tract between one time when one or more independent variables have one value or set of values and another time when that value or set of values is different.
Information capacity of the channel and net	Maximum number of bits per second that can be transmitted over a neural tract
Distortion of the channel and net	Amount of alteration in the wave-form or relationships between various frequency components of a signal transmitted over a neural tract.
Signal-to-noise ratio in the channel and net	The ratio in decibels between the amplitude of the signal and the background noise in a neural tract
Rate of processing of information over the channel and net	Number of bits of information transmitted over a neural tract in a specific second
Lag in channel and net processing	Number of seconds between input and output of a signal over a neural tract
Costs of channel and net processing	Amount of matter-energy expended in a specific transmission of information over a particular neural tract

DISCUSSION

Saaty: I find the classification of hierarchy fascinating and I wish to ask a question. I am curious about the 19 components in each level? Are these independent components or do they interact so that they form clusters? Is perhaps their a total number of smaller? The reason for this is that playing around with ideas as I talked about this morning - if you are at a higher significance level and if you assume that nature operates in a consistent fashion, my total number is more between 40 and 50 and I find the number of 132 a little high and I was just curious about it.

Miller: Well, I didn't decide on the number of sub-systems - God or Darwin did. It seems to me that they are in 3 clusters which I indicated in the 3 columns of my basic chart. There is an input out-put relationship of matter and energy. There is a flow through sub-system which processes it in various ways like the assembly line. That is one of the clusters of sub-systems. There is in-put, throughput and output of information. That's the processing that goes on internally and that is the second. There is, as I pointed out, two functions: - The boundary function and the reproducing function-that's involved in both. So if I were to select a cluster of sub systems it would be those 3.

Coombs: You mentioned an essential element of the control system is a reward or penalty. Can you interpret that in terms of training, loyalty esprit de corps, things of that sort, which many of us think about?

Miller: Well, there is a rather gross and base level, known as food and money. You cannot continue any military activity of any civilian activity without adequate inputs of food water and oxygen. In modern times we have something known as legal tender or money, which can be transfered from one purpose or another so you can buy either some of those necessities or other types of necessities or luxuries with the same money. So money represents the opportunity to choose between various inputs you may wish to have.

You have to have that sort of incentive to operate any system. You have even the love relationship between a mother and a child that is based on a input output relationhip primarily at the beginning. In a maturational species like ours where the infant is dependent for a period of time on the mother - unlike chicks which are not dependent in a precocious species like that - you have a parasitism from the beginning in which one individual is dependent on another one for certain inputs or outputs - the same thing when you get older, as an older person in a nursing home, you are dependent on a input output function from the group - that is, the nursing group which is taking care of you. You have a paracitist situation in old age often times.

The same thing is true in military organizations, business corporations or universities where ever it may be, that a basic reward systems is operative. It may be a reward for promotion in rank, promotion in salary or it may be just a promotion in prestige in status or recognition. This often as we have found out by in the fact that we now give our military all sorts of ribbons to wear and so on, because this apparently does effect motivation and does effect recognition, is a very important factor. Human beings are so built apparently that you can get what you call autonomous drives, learned drives. They are based I believe on the basic biological drives originally but if you learn to be as satisfied with recognition - a salute for example as you are, in a sense, with a piece of apple pie. Therefore you can get an instinctive operative, a system operating and we do - which can get men into battle even death apparently willing or voluntarily, in order to receive even posthumous rewards or recognition or in order not to be punished, which is, of course, the negative side to all of this. There are a whole lot of studies on reward and punishment which indicate this is a very rough figure and not reliable in any sense. Perhaps reward is 20 times as effective in motivation behavior as punishment. So there are 2 types - there are the basic drives we call biological and social drives and then there are the learned

drives and they are both effective in motivating behavior and could be used and are used in any living system that I know of.

I wish we could get one question on the topic of this conference. Given another hour I could talk about what we are here for.

Lehmann: You know I think you have hit the mark. I don't think people are wanting for a lack of ideas on how you applied this to Tactical Command and Control.

Question: I wonder if you have any example of a specific system which is somewhat related to this group which you could cite which has been tried or applied?

Miller: Well yes, we have in our graduate program at the University of Louisville a general exercise that our master's level student go through, like an early exercise that is applied on a conceptional approach. We assign to them an organization and say, "Go out and study it. Get a map of it in space - a regular map - and draw on it in different colors the 19 sub systems and come back when you have been able to do it and write a paper defending your break-down of our universe into the 19 sub systems." They do that and then they go on to the next step and we say, "Which of these is the system total potential?" That's another technical term we use that I didn't use that is, completely independent. For example: Astronauts in space have to be totally potential - they have to have all capability of life with them. But we are not totally potential here, for example. This group, as long as it is in Airlie House, is dependent for matter inputs and outputs , fortunately, on the Airlie House hospitality, so we are not a totally potential group. You have to identify to what extent this particular system you are looking at is dependent on the intrastructure of the society of which it is dependent. If you closed off its boundries, in other words, how long would it be able to continue to live. Some of them might consider New York would terminate over night because it is so un-potential, the opposite of total potential, that closing its boundries for 24

hours would cause fantastic disturbance. On the other hand you take a primitive town say in far out Turkey. - You could put a seige on that and it might be able to continue for a year. So you have analyses of this sort which you can make - which we do make as early exercises in our advance classes - which are applications to types of problems I think some you you are interested in. Thank you.

INTERACTION AND IMPACTS IN HIERARCHICAL SYSTEMS

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1.0 *Introduction.* The scientific literature of hierarchies has driven home to physical, behavioral and systems scientists and particularly to people interested in organization theory, the lesson that a hierarchy is the single most powerful mental construct for studying complex systems. Whether one is simply interested in understanding the actual structure and flow of a system or whether he is concerned with the functional interactions of its components, a hierarchical model of that system must inevitably be examined. Hierarchic organization is crucial to the synthesis and survival of large systems. Hierarchic systems have common properties that are independent of their specific content.

There are several kinds of hierarchies, the simplest of which are dominance hierarchies which descend like an inverted tree with the boss at the root, followed by successive levels of bossing. Another kind are holarchies which are essentially dominance hierarchies with feedback. Chinese box (or modular) hierarchies grow in size from the simplest elements or components (the inner boxes) to larger and larger aggregates (the outer boxes). In biology, neogenetic hierarchies are of interest because they have successive newly emerging top levels through evolution. We shall concentrate our attention on dominance hierarchies, although the theory described below is being generalized to the other hierarchical forms.

Even if the structure of a system is characterized by a network of a high dimension of complexity, when it is analyzed according to function and purpose, it takes on the simple form of a dominance hierarchy with descending levels of decreasing importance.

What interests us here is to provide an informal report on research leading to a useful theory for analyzing the impacts of different levels, representing subsystems, of a system, characterized as a hierarchy, on the entire hierarchy and conversely. The theory also enables us to study the stability of a hierarchy to perturbations in both structure and function.

The development of the theory has called for a new and general method of measurement yielding ratio scales. This method has been successfully tested by way of validation in optics, heat and similar phenomena. It has also been applied in economics to estimate the relative wealth of nations (correlating closely with their GNP's) and in politics to determine a measure of influence of nations.

An intrinsic useful by-product of the theory is an index of consistency which provides information on how serious are violations of numerical (cardinal) and transitive (ordinal) consistency. The result could be to seek additional information and reexamine the data used in constructing the scale in order to improve consistency. Such an index is not available in other procedures for the construction of ratio scales. The method also utilizes, for reasons suggested by consistency requirements, reciprocal entries ($a_{ji} = 1/a_{ij}$) in pairwise comparison matrices instead of the traditional $a_{ji} = -a_{ij}$ used for construction of

interval scales. This is both an intuitively reasonable assumption and turns out to be an asset in using the basic theory of Perron-Frobenius to establish the existence of a non-negative unique solution as a ratio scale.

Our approach reduces to the study of two related problems: The first is concerned with measurement. Suppose we are given a set of objects which are all sufficiently light and can be lifted by hand. We wish to estimate their relative weights. One way would be to directly guess the weight of each object in pounds for example, by lifting it (perhaps using the lightest one as the standard), comparing the whole class, and then dividing the weight of each by the total to get its relative weight. Another method which utilizes more of the available information in the experiment is to compare the objects in pairs, such as lifting one and then lifting another and then back to the first and then again the second and so on until we have formulated a judgment as to the relative weight (ratio) of each pair of objects. The problem then is to find these pairwise comparisons. There is such a way and it will be discussed in detail later. The second process has the advantage of focusing on two objects at a time and on how they relate to each other. It also uses redundant information since each object is methodically compared with every other.

For problems where there is no scale to validate the result, the pairwise comparison process can prove to be an asset because in a sense it is simpler in each of its steps than the first.

All measurement including those which make use of instruments are subject to experimental error and

to error in the measuring instrument. A serious effect of error is that it can and often does lead to inconsistent conclusions. A simple example of the consequence of error in weighing objects is to find that A is heavier than B, and B is heavier than C but C is heavier than A. This can happen particularly when the weights of A, B, and C are close, and the instrument is not fine enough to distinguish between them. Lack of consistency may be serious for some problems but not for others. For example, if the objects are two chemicals to be mixed together in exact proportion to make a drug, inconsistency may mean that proportionately more of one chemical is used than the other possibly leading to harmful results in using the drug.

But perfect consistency in measurement even with the finest instruments is difficult to attain in practice and what we need is a way of evaluating how bad it is for a particular problem.

Since consistency is a central question in concrete measurement, in judgments, and in the thinking process, an effective measure of consistency in applying numerical ratio scales, is an incentive for developing scales in areas where we do not have instruments of measurement. In passing we note that measuring instruments are not and cannot be means of absolute measurement but themselves have been the object of scientific research. If these instruments are for any reason inadequate (and one can always devise an experiment for which there is no satisfactory instrument for measurement) then we must keep inventing new instruments. It is not difficult to imagine some important experiment for which no sufficiently fine instrument can ever be found from which consistent answers can always be obtained. In that case the

entire problem is shifted to the study of consistency and evaluating the seriousness of inconsistency.

The process of measurement by pairwise comparisons leads in a natural way to the problem of consistency, enabling us to characterize or say exactly what *we mean by consistency, and to develop a measure for* how serious inconsistency is.

In the measurement of physical quantities it is usually possible to set down a dimension or property such as length which remains the same (relativity notwithstanding) in time and space and devise instruments to measure this property. Naturally it would be more difficult to make an instrument which adjusts its scale to changing circumstances before doing measurement. For example, length and mass vary at speeds near that of light and an instrument that directly measured these properties at near the speed of light would require some kind of variable scale.

This is precisely the problem in the social sciences. When we deal with properties that change not only in time and space but also, (and far more seriously) in conjunction with other properties, their meaning also changes. We cannot improvise universal scales for social events. Social phenomena are even more complicated than physical phenomena because they are harder to replicate in abundance. Too much control must be imposed and controls in themselves often destroy the very social behavior one is trying to measure. Our judgments must be sufficiently flexible to take into consideration the contextual setting of the property being measured.

Consider the problem of measuring achievement and happiness. Both may be called relative properties

in that the unit of measurement may have to be adjusted to compare, for example, the degree of happiness in one setting with that in another and as we shall see it is possible to do this with the pairwise comparison technique. What we need to recognize is that an instrument which varies its scale with the relativeness of the circumstance can be the human mind itself, particularly, if it turns out that its measurement is sufficiently consistent to satisfy the requirements of the particular problem. The intensity of our feelings serves as a scale-adjustment-device to put the measurement of some objects on a commensurate scale with that of other objects. In fact as the mind improves its precision it becomes the required tool for relative measurement as no instrument except our very personally designed one (our own mind) can be made to suit our particular experience and viewpoint. A group must coordinate their outlook to produce results acceptable (in some sense) to them.

But the problem does not end here. By way of validation whatever method of scaling we develop must so far as it is possible, reproduce results consistent with those known in physical and in any other area where there are scales for measurement. This should serve to encourage extending the method to the "softer" areas of the social sciences.

We now turn to our second problem which is concerned with providing greater stability and invariance to social measurement. Granted that the dimensions or properties are variable how do we measure the impact of this variability on still other higher level properties, and in turn these on still higher ones. It turns out that for a very wide class of problems we can usually identify overall properties (or one

property) which remain the same for sufficiently long duration of an experiment. This approach leads us to the measurement and analysis of impacts in hierarchies.

The theory of hierarchies says that complex systems problems are hierarchic in nature with their elements occupying different levels of the hierarchy and that we can study the contributions or impacts of these elements on the hierarchy through the use of measurement. We can also study the invariance of the measurement by changing the levels of the hierarchy. The results of the measurement may be used to enhance the stability of the system or to design new goal-oriented systems. They can also be used (as priorities) to allocate resources.

As we said before, the theory of hierarchies provides models for studying interactions between elements and components (levels) of a system. The assumption here is that measurement derives from judgments based on observation and understanding. These observations enable measurement from comparisons (not from absolutes). And also the comparisons result in separating objects or phenomena into comparability classes which are levels of the hierarchy. Measurement is used to study interactions among comparability classes. Furthermore the objects in any class are compared according to their impact on each element of the immediately higher level. This is equivalent to measuring how strongly each element possesses a property or attribute belonging to a different level. For each property the comparison shows the relative strength of an object or property (as a generic term) in a level. The hierarchical structure makes it possible to perpetrate the impact study up and down the hierarchy.

Since 1971 about thirty applications have been made of the theory of hierarchies ranging from energy studies for the government to designing a transport system for the Sudan and to planning with the board of a corporation towards more desirable futures. Let us now turn to a few elementary examples to illustrate the basic ideas.

2.0 *Measurement*. It is inevitable, in the study of hierarchies, that the problem of measurement should arise. If we are interested in measuring the impact of a set of elements in a level of the hierarchy on each of the elements of the next higher level, we must be able to measure the behavior of the elements or their contribution to the elements of the higher level. Here we need to recognize that all measurement which leads to a standard scale must begin with observation; in fact, many observations. When the measurement derives from preferences based on abstract knowledge or feeling, the latter must serve in some reliable fashion the role of direct observation. Thus, our analytical approach must have an appeal to a wide variety of needs in measurement. Its validation in areas where measurement is available would serve to increase confidence in its use in new areas.

It is clear that in order to develop a scale of measurement we must learn to compare. With comparison there is associated a relative scale for the objects being compared. When a sufficiently large number of objects has been considered in the comparison process and analytical or judgmental agreement reached on the values in the comparison, the resulting scale acquires greater universality and autonomy.

We distinguish between objects or between

phenomena because they have different properties or occupy different positions in space and time. The distinction is usually made with respect to several properties at the same time. In fact, we need to know the relative standing of each object according to all the properties; we must distinguish between the properties themselves. This process of distinguishing between things is a process of comparison. If the objects are independent, all comparisons can be reduced to pairwise comparisons. If they are dependent, then the dependence itself must be taken into consideration in the final weighting.

When we are interested in causal explanation, we find that phenomena can be arranged according to precedence: something must happen before something else can happen. Ordering leads to hierarchical type of structures in which first causes occupy higher levels of the hierarchy.

The ordering is a first step in the process of measuring variations among the objects being compared according to each of several properties. What is usually desired is stronger than simple order. In scientific measurement more often than not we seek measurement on ratio scales. This is what we will discuss here.

When we deal with phenomena for which there are no known or widely agreed upon scales and instruments of measurement, it becomes a matter of judgment to estimate numerical values for comparison. As more people interact and agree on these judgments, a scale (implicit or explicit) gradually evolves and eventually acquires universality. Examples are our scales for measuring distance, time, weight and economic

value. In some areas of social interaction it is useful to expedite the process of measurement by making available fundamental tools which by way of validation yield the same results in areas where measurement is already available.

Works on scaling abound. The results on ratio scales are more scarce. Among them we have found interesting accounts by S.S. Stevens [17], Churchman and Ratoosh [2], Torgerson [19], Shepard [14], and Krantz [4].

We focus attention on a single level of a hierarchy and first study the relation of dominance of its elements with respect to a single property. We will then study the more general problem of the impact of all elements of a level on the entire hierarchy. We have already alluded in the introduction to a large number of other results and interactions which can be studied this way. It seems adequate to me to only show how this fundamental step can be carried out. What we will do here is to motivate the method of generating a ratio scale from pairwise comparisons and generalize the result to a hierarchy. The full justification of the approach is found in a technical paper appearing elsewhere.

3.0 *The Paradigm Case Consistency*. Assume that n activities are being considered by a group of interested people. We assume that the group's goals are:

a. to provide judgments on the relative importance of these activities;
b. to insure that the judgments are quantified to an extent which also permits a quantitative interpretation of the judgments among all activities.

Clearly, goal b will require appropriate technical assistance.

Our goal is to describe a method for deriving, from the group's quantified judgments (i.e., from the relative values associated with pairs of activities), a set of weights to be associated with individual activities; in a sense defined below, these weights should reflect the group's quantified judgments. What this approach achieves is to put the information resulting from a and b into usable form without deleting information residing in the qualitative judgments.

Let $C_1, C_2, \ldots, C_n$ be the set of activities. The quantified judgments on pairs of objectives C_i, C_j are represented by an n-by-n matrix

$$A = (a_{ij}), \ (i,j = 1, 2, \ldots, n).$$

Having recorded the quantified judgments on pairs (C_i, C_j) as numerical entries a_{ij} in the matrix A, the problem now is to assign to the n contingencies $C_1, C_2, \ldots, C_n$ a set of numerical weights $w_1, w_2, \ldots, w_n$ that would "reflect the recorded judgments."

In order to do so, the vaguely formulated problem must first be transformed into a precise mathematical one. This essential, and apparently harmless step, is the most crucial one in any problem that requires the representation of a real-life situation in terms of an abstract mathematical structure. It is particularly crucial in the present problem where the representation involves a number of transitions that are not immediately discernible. It appears, therefore, desirable in the present problem to identify the

major steps in the process of representation and to make each step as explicit as possible in order to enable the potential user to form his own judgment on the meaning and value of the method in relation to his problem and his goal.

It is convenient to first get a simple question out of the way. The matrix A of quantified judgments a_{ij} may have several, or only few, non-zero entries. The question arises: how many non-zero entries (i.e., how many quantifiable judgments) are necessary in order to insure the existence of a set of weights that is meaningful in the context of the problem? The obvious answer is: it is necessary that there be a set of non-zero entries that interconnects all activities in the sense that for every two indices, i, j, there should be some chain of non-zero entries connecting i with j:

$$a_{ii_1}, a_{i_1i_2}, a_{i_2i_3}, \ldots, a_{i_kj}, \tag{3.0}$$

When $a_{ij} \neq 0$, a_{ij} itself is such a chain of length 1. (Such a matrix $A = (a_{ij})$ corresponds to what is known as a strongly connected graph.) This gives precise content to the formulation of goal b.

The major question is the one concerned with the meaning of the vaguely formulated condition in the statement of our goal: ..."these weights should reflect the group's quantified judgments." This presents the need to describe in precise, arithmetic terms, how the weights w_i should relate to the judgments a_{ij}; or, in other words, the problem of specifying the conditions we wish to impose on the weights we seek in relation to the judgments obtained. The desired description is developed in 3 steps, proceeding from the simplest special case to the general one.

Assume first that the "judgments" are merely the result of precise physical measurements. Say the judges are given a set of pebbles, $C_1, C_2, \ldots, C_n$ and a precision scale. To compare C_1 with C_2, they put C_1 on a scale and read off its weight--say, $w_1 = 305$ grams. They weigh C_2 and find $w_2 = 244$ grams. They divide w_1 by w_2, which is 1.25. They pronounce their judgment, "C_1 is 1.25 times as heavy as C_2" and record it as $a_{12} = 1.25$. Thus, in this ideal case of <u>exact measurement</u>, the relations between the weights w_i and the judgments a_{ij} are simply given by:

$$\frac{w_i}{w_j} = a_{ij} \quad \text{(for } i, j = 1, 2, \ldots, n) \qquad (3.1)$$

or by

$$\frac{a_{ij} w_j}{w_i} = 1 \quad i, j = 1, \ldots, n$$

from which we have the fact that w_i may be obtained as an average over $(a_{i1}w_1, a_{i2}w_2, \ldots, a_{in}w_n)$ which we write in the form

$$\sum_{j=1}^{n} a_{ij} w_j / w_i = n \quad i = 1, \ldots, n \qquad (3.2)$$

indicating that all such ratios have the same value n.

In matrix notation our problem takes the form

$$Aw = nw \qquad (3.3)$$

This is an eigenvalue problem which may be interpreted as follows: Given the linear transformation A, find the weight vector w such that it is a fixed point under $\frac{1}{n}$ A or simply that it is dilated by a factor n under A.

It is worthwhile investigating the properties of matrix A and whether the problem (3.3) has a unique

solution w with nonnegative entries w_i. Thus it would be useful to examine the paradigm case in greater depth.

Let us first note that the matrix A has the property that each of its rows can be generated from any one of them by multiplying by a different constant. It follows that the rank of A is unity. This observation, together with the fact that the main diagonal elements are all equal to unity, enables us to prove that this is equivalent to the property (called the consistency property) $a_{ij}a_{jk} = a_{ik}$ satisfied by all the elements of A. Now we turn to the solvability of the eigenvalue problem (A-nI) w=o. This homogeneous system has a nontrivial solution if and only if the determinant of the matrix (A-nI) is zero from which it follows that n must be an eigenvalue of A. Now it is known that the sum of the eigenvalues of a matrix is equal to its trace $\sum_{i=1}^{n} a_{ii}$. The trace of A in the paradigm case is n. Since the rank of A is unity all but one of its eigenvalues is zero. Thus the maximum eigenvalue of A is n.

It would be unrealistic to require the relations (3.2) to hold in the general case. Imposing these stringent relations would, in most practical cases, make the problem of finding the w_i (when a_{ij} are given) unsolvable. Firstly, even physical measurements are never exact in a mathematical sense, and hence, allowance must be made for deviations; and secondly, because of error in human judgments, these deviations are considerably larger. Thus, it is not reasonable to expect the consistency condition to always hold.

In order to see how to make allowance for deviations, consider the i^{th} row in the matrix A. The entries in that row are:

$$a_{i1}, a_{i2}, \ldots, a_{ij}, \ldots, a_{in}$$

In the paradigm case these values were the same as the ratios

$$\frac{w_i}{w_1}, \frac{w_i}{w_2}, \ldots, \frac{w_i}{w_j}, \ldots, \frac{w_i}{w_n}$$

Hence, in that case, if we multiply the first entry in that row by w_1, the second entry by w_2, and so on, we would obtain

$$\frac{w_i}{w_1} w_1 = w_i, \frac{w_i}{w_2} w_2 = w_i, \ldots, \frac{w_i}{w_j} w_j =$$

$$w_i, \ldots, \frac{w_i}{w_n} w_n = w_i$$

The result is a row of identical entries

$$w_i, w_i, \ldots, w_i,$$

whereas, in the general case, we would obtain a row of entries that represent a statistical scattering of values around w_i which amounts to a perturbation of the entries a_{ij} in row i.

We should note of course, that large changes in the values of a_{ij} could mean a drastic departure from consistency and more importantly from the exact values of the ratios w_i/w_j. We are interested in deriving the scale of w's under the assumption that the judges have adequate information to assist in the process. Thus, the question before us now is what happens with moderate perturbations of the coefficients a_{ij}.

A useful theorem from matrix theory says that the eigenvalues $\lambda_1, \ldots, \lambda_n$ of a matrix $B = (b_{ij})$ depend continuously on the coefficients $b_{11}, b_{12}, \ldots, b_{nn}$.

It follows that a perturbation of the entries a_{ij} in the paradigm case would keep the largest eigenvalue in the neighborhood of n and the remaining ones close to zero. The problem becomes: find w which satisfies

$$Aw = \lambda_{max} w$$

of which (3.3) is a special case when A is consistent. This is also the expression we would obtain from the expression in (3.2) involving the weighted mean. We note that to each λ_{max} corresponds a large number of matrices. Some of these matrices may be far from consistent. Thus, the same eigenvector can arise from many matrices. Among all such matrices we shall be interested in those whose largest eigenvalue is n or those for which $\frac{\lambda_{max}-n}{n-1}$ is small.

If we assume that the values are estimated precisely, i.e., $a_{ij} = w_i/w_j$, it is then sufficient to require consistency of the judgment matrix to obtain such equality. From the consistency condition $a_{ij}a_{jk} = a_{ik}$ we have for the main diagonal entries $a_{ii} = 1$ and the reciprocal relations $a_{ji} = 1/a_{ij}$. In general, we do not expect 'cardinal' consistency to hold everywhere in the matrix because people's feelings do not conform to an exact formula such as the one just given. Nor do we expect 'ordinal' consistency as people may not want to behave that way (see below). However, to improve consistency in the numerical

judgments, whatever value a_{ij} is assigned in comparing the ith activity with the jth one, the reciprocal value is assigned to a_{ij}, thus putting $a_{ji} = \frac{1}{a_{ij}}$. Roughly speaking, if one activity is judged to be α times stronger than another, then the latter is only $1/\alpha$ times as strong as the former. It can be easily seen that when we have consistency, the matrix has unit rank and it is sufficient to know one row of the matrix to construct the remaining entries. For example, if we know the first row then $a_{ij} = a_{1j}/a_{1i}$ (a rational assuming, of course, that $a_{1i} \neq 0$ for all i). We have found the interesting theorem that a matrix of judgments which uses reciprocals is consistent if and only if $\lambda_{max} = n$. We also have $\lambda_{max} \geq n$ always. Thus $\lambda_{max}-n$ provides a measure of departure from consistency and indicates when judgments should be revised. By comparing $\lambda_{max}-n$ with $d\lambda_{max}$ for extremely bad results, one can tell how serious the inconsistency is.

We do not insist that judgments be consistent and, hence, they need not be transitive; i.e., if the relative importance of C_1 is greater than that of C_2 and the relative importance of C_2 is greater than that of C_3, then the relation of importance of C_1 need not be greater than that of C_3, a common occurrence in human judgments. An interesting illustration is afforded by tournaments regarding inconsistency or lack of transitivity of preferences. A team C_1 may lose against another team C_2 which has lost to a third team C_3; yet C_1 may have won against C_3. Thus, team behavior is inconsistent--a fact which has to be accepted in the formulation, and nothing can be done about it.

We now turn to a question of what numerical scale to use in the pairwise comparison matrices. Whatever problem we deal with we must use numbers that are sensible. From these the eigenvalue process would provide a scale. As we said earlier, the best argument in favor of a scale is if it can be used to reproduce results already known in physics, economics or whatever area that there is a scale. Enough has been written in this field to fill many large volumes. However, one of the most appealing works in the area of the existence of ratio scales based on an axiomatic approach to psychophysical measurement is due to David Krantz [4]. We refer the reader to his work. Briefly, comparing our theory with Krantz's work suggests that this approach is on the right track in producing realistic answers.

Our choice of scale hinges on the following observation. Roughly, the scale should satisfy the requirements:

1. It should be possible to represent people's differences in feelings when they make comparisons. It should also represent all distinct shades of feeling that people have.

2. It must satisfy the functional equation

$$f(x)f(\tfrac{1}{x}) = 1 \text{ with } f(1) = 1$$

The simplest nonconstant function which satisfies this equation is $f(x) = x$.

3. If we denote the scale values by $x_1, x_2, \ldots, x_n$, then it would be desirable that $x_{i+1} - x_i = 1 \quad i=1, \ldots, n-1$. The reasons for this are

a) we need uniformity between differences to make sure that the scale covers all judgments. We require that

subject must be aware of all objects at the same time.

b) We agree with the psychological experiments which show that an individual cannot simultaneously compare more than seven objects (plus or minus two) without being confused.

c) If a unit difference between successive scale values is all that we allow, then by requiring uniformity and using the fact that $x_1=1$ for the identity comparison, it follows that the scale values will range from one to nine.

As a preliminary step towards the construction of an intensity scale of importance for activities, we have broken down the importance ranks as follows:

Intensity of Importance	Definition	Explanation
1*	Equal Importance	Two activities contribute equally to the objective.
3	Weak importance of one over another.	The judgment favors one activity over another, but it is not conclusive.
5	Essential or strong importance.	The judgment and logical criteria show that one is more important.
7	Demonstrated importance.	Conclusive judgment as to the importance of one activity over another.
9	Absolute importance.	The judgment in favor of one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgments.	When compromise is needed.

*On occasion in 2 by 2 problems, we have used $1 + \varepsilon$, $0 < \varepsilon < \frac{1}{2}$ to indicate very slight dominance between two nearly equal activities.

Intensity of Importance	Definition	Explanation
Reciprocals of above non-zero numbers	If activity i has one of the above non-zero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i.	See below.
Rationals	Ratios arising from the scale.	If consistency were to be forced by obtaining n numerical values to span the matrix.

In using this scale the reader should recall that we assume that the individual providing the judgment has knowledge about the relative values of the elements being compared whose ratio is ≥ 1, and that the numerical ratios he forms are nearest integer approximations scaled in such a way that the highest ratio corresponds to 9. We have assumed that an element with weight zero is eliminated from comparison. This, of course, need not imply that zero may not be used for pairwise comparisons. Reciprocals of all scaled ratios that are ≥ 1 are entered in the transpose positions (not taken as judgments) with a zero for the transpose of a zero entry. Note that the solution of the problem remains the same if we multiply the unit entries on the main diagonal by a constant. Thus, despite scaling, each main diagonal element may continue to equal unity. In practice, one way or another, the numerical judgments will have to be approximations, but how good is the question at which our theory is aimed.

A typical question to ask in order to fill in the entries in a matrix of comparisons is: Consider two properties i on the left side of the matrix and another j on the top; which of the two has the property under discussion more, and how strongly more (using the same values 1 to 9). This gives us a_{ij}. The reciprocal value is then automatically entered for a_{ji}.

Example 1. The rate at which a source emits light energy evaluated in terms of its visual effects is spoken of as a light flux. The illumination of a surface is defined as the amount of light flux it receives per unit area.

The following experiment was conducted in search of a relationship between the illumination received by four identical objects (placed on a line at known distances from a light source) and of the distance from the source. The comparison of illumination intensity was performed visually and independently by two sets of people. The objects were placed at the following distances measured in yards from the light source: 9, 15, 21, and 28. In normalized form, these distances are: .123, .205, .288, .384.

The two matrices of pairwise comparisons of the brightness of the objects labelled in increasing order according to their nearness to the source are:

Relative Visual Brightness (1st Trial)

	C_1	C_2	C_3	C_4
C_1	1	5	6	7
C_2	$\frac{1}{5}$	1	4	6
C_3	$\frac{1}{6}$	$\frac{1}{4}$	1	4
C_4	$\frac{1}{7}$	$\frac{1}{6}$	$\frac{1}{4}$	1

Relative Visual Brightness (2nd Trial)

	C_1	C_2	C_3	C_4
C_1	1	4	6	7
C_2	$\frac{1}{4}$	1	3	4
C_3	$\frac{1}{6}$	$\frac{1}{3}$	1	2
C_4	$\frac{1}{7}$	$\frac{1}{4}$	$\frac{1}{2}$	1

Relative Brightness Eigenvector (1st Trial)	Relative Brightness Eigenvector (2nd Trial)
.62	.62
.24	.22
.10	.10
.05	.06
$\lambda = 4.39$	$\lambda = 4.1$

Reciprocal of Corresponding Normalized Distance Square	Normalized Reciprocal Distance Square
.66	.61
.24	.22
.12	.11
.07	.06

Note the sensitivity of the results as the object is very close to the source for then it absorbs most of the value of the relative index and a small error in its distance from the source yields great error in the values. What is noteworthy from this sensory experiment is the observation or hypothesis that the observed intensity of illumination varies (approximately) inversely with the square of the distance. The more carefully designed the experiment the better results obtained from the visual observation. Statistical measures may be used to confirm the closeness of the observed results with the actual.

Example 2: Distance Estimation Through Air Travel Experience

The Eigenvalue Method was used to estimate the relative distance of six cities from Philadelphia by making pairwise comparisons between them as to which was strongly farther from Philadelphia.

It is interesting to note that the cities cluster into three classes--the near ones to Philadelphia, Montreal, and Chicago; the intermediate ones: San Francisco and London; and the far ones cause a great perturbation in the entire system because their eigenvector components change comparatively slightly but as the increment is distributed among the others, their relative values can be altered considerably.

Probably the problem should be reformulated with clustering taken into account. It leads to a consideration of clusters on the same level. The elements in each cluster are first compared and then the clusters would be themselves compared to obtain the appropriate weights.

Now for the example. The first three tables give the original judgments matrix with charges made in it in the other two; and the fourth table gives the results.

M1: Original Judgment Matrix

Eigenvector	Comparison of Distances of Cities from Philadelphia	Cairo	Tokyo	Chicago	San Francisco	London	Montreal
.267	Cairo	1	1/4	8	6	4	8
.482	Tokyo	4	1	9	7	5	9
.033	Chicago	1/8	1/9	1	1/3	1/5	2
.062	San Francisco	1/6	1/7	3	1	1/4	4
.131	London	1/4	1/5	5	4	1	6
.025	Montreal	1/8	1/9	1/2	1/4	1/6	1

M2: 2nd Judgment Matrix (✓ indicates changes from M1)

Eigenvector	Comparison of Distances of Cities from Philadelphia	Cairo	Tokyo	Chicago	San Francisco	London	Montreal
.259	Cairo	1	1/4	8	4 ✓	4	7 ✓
.461	Tokyo	4	1	7 ✓	5 ✓	5	8 ✓
.037	Chicago	1/8	1/7	1	1/3	1/5	2
.073	San Francisco	1/4	1/5	3	1	1/4	4
.142	London	1/4	1/5	5	4	1	6
.028	Montreal	1/7	1/8	1/2	1/4	1/6	1

M3: 3rd Judgment Matrix (√ indicates changes from M1 - x indicates changes from M2)

Eigenvector	Comparison of Distances of Cities from Philadelphia	Cairo	Tokyo	Chicago	San Francisco	London	Montreal
.263	Cairo	1	1/3	3	3 √x	3 √x	7
.397	Tokyo	3 √x	1	9 x	3 √x	3 √x	9 x
.033	Chicago	1/8	1/9	1	1/6	1/5	2
.116	San Francisco	1/3	1/3	6 √x	1	1/3	6
.164	London	1/3	1/3	5	3 √x	1	6
.027	Montreal	1/7	1/9	1/2	1/6	1/6	1

City	Distance to Philadelphia in Miles	Normalized Distance	Eigenvector of M1	Eigenvector of M2	Eigenvector of M3
Cairo	5729	.278	.267	.259	.263
Tokyo	7449	.361	.482	.461	.397
Chicago	660	.032	.033	.037	.033
San Francisco	2732	.132	.062	.073	.116
London	3658	.177	.131	.142	.164
Montreal	400	.019	.025	.028	.027

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PROCEEDINGS OF THE WORKSHOP ON DECISION INFORMATION FOR TACTICA--ETC(U)

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4.0 *Hierarchies and Their Properties*. Although the notion of a hierarchy is old, our method of measurement in hierarchical structures is new. It cannot be compared with any analytical macro models because so far all such modelling manages to pull all its variables into a single level. What we need to do is apply our analysis to problems whose hierarchical structure is carefully defined and note the results for their relevance and validity. Methods involving optimization with multiple objectives do not offer justification for the use of ratio scaling. Careful examination of that literature has not benefited our approach to hierarchies. Perhaps one of the most interesting analytical works which have enriched the concept of a hierarchy is the paper by H. Simon and A. Ando [15] from which the first author derived many insights into hierarchies for his subsequent works on the subject.

Any system is a large matrix of interactions between its components in which most of the entries are (close to) zero. Ordering those entries according to their orders of magnitude, a distinct hierarchic structure, is discerned. In fact, this arrangement of the elements of a system in an incidence type matrix can be used to identify the levels of a hierarchy. The stability, or functional efficacy of the higher level structures, can be made relatively independent of the detail of their microscopic components by virtue of hierarchic structure. Such a structure also provides explanation as to why elements in any given level can preserve a measure of independence to adapt their structure and function to the environment without destroying their usefulness to the system.

The laws characterizing different levels of a

hierarchy are generally different. The levels differ both in structure and function. The proper functioning of a higher level depends on the proper functioning of the lower levels. The basic problem with a hierarchy is to seek understanding at the highest levels from interactions of the various levels of the hierarchy rather than directly from the elements of the levels. At this stage of development of the theory the choice of levels in a hierarchy generally depends on the knowledge and interpretation of the observer. Rigorous methods for structuring systems into hierarchies are gradually emerging in the many areas of the natural and social sciences and, in particular, in general systems theory as it relates to the planning and design of social systems.

What is a Hierarchy?

Definition 1. An ordered set is any set S with a binary relation $\leq$ which satisfies the reflexive, anti-symmetric, and transitive laws:

Reflexive: For all x, $x \leq x$;

Anti-symmetric: If $x \leq y$ and $y \leq x$, then $x = y$;

Transitive: If $x \leq y$ and $y \leq z$, then $x \leq z$.

For any relation $x \leq y$ (read, y includes x) of this type, we may define $x < y$ to mean that $x \leq y$ and $x \neq y$. y is said to cover (dominate) x if $x < y$ and if $x < t < y$ is possible for no t.

Ordered sets with a finite number of elements can be conveniently represented by a directed graph. Each element of the system is represented by a vertex so that an arc is directed from a to b if $b < a$.

Definition 2. A simply or totally ordered set (also called a chain) is an ordered set with the additional property that if $x, y \in S$ then either $x \leq y$ or $y \leq x$.

Definition 3. A subset E of an ordered set S is said to be bounded from above if there is an element $s \varepsilon S$ such that $x \leq s$ for every $x \varepsilon E$. The element s is called an upper bound of E. We say E has a supremum or least upper bound in S if E has upper bounds and if the set of upper bounds U has an element u_1 such that $u_1 \leq u$ for all $u \varepsilon U$. The element u is unique and is called the supremum of E in S. The symbol sup is used to represent a supremum.

Similar definitions may be given for sets bounded from below, a lower bound and infimum. The symbol inf is used.

Definition 4. A sup-lattice is an ordered set in which any two elements x and y have a supremum. An inf-lattice in an ordered set in which any two elements x and y have an infimum. A lattice is an ordered set that is both a sup-lattice and an inf-lattice.

There are many ways of defining a hierarchy. The one which suits our needs best here is the following:

We use the notation $x^- = \{y|x \text{ covers } y\}$ and $x^+ = \{y|y \text{ covers } x\}$, for any element x in an ordered set.

Definition 5. Let H be a finite sup-lattice with largest element b.

H is a hierarchy if it satisfies the conditions

a) There is a partition of H into sets L_k, $k = 1, \ldots, h$ where $L_1 = \{b\}$.

b) $x \varepsilon L_k$ implies $x^- \subset L_{k+1}$ $\quad k = 1, \ldots, h-1$.

c) $x \varepsilon L_k$ implies $x^+ \subset L_{k-1}$ $\quad k = 2, \ldots, h$.

For each $x \varepsilon H$, there is a weighting function $w_x: x^- \to [0,1]$ such that $\sum_{y \varepsilon x^-} w_x(y) = 1$.

The sets L_i are the <u>levels</u> of the hierarchy, and the function w_x is the <u>priority function</u> of the elements in one level with respect to the objective x. We observe, that even if $x^- \neq L_k$ (for some level L_k), w_x may be defined for all of L_k, by setting it equal to zero for all elements in L_k not in x^-.

Definition 6. A hierarchy is <u>complete</u> if, for all $x \varepsilon L_k$, $x^+ = L_{k-1}$, for $k = 2, \ldots, h$.

We can now state the central question:

Basic Problem: Given any element $x \varepsilon L_\alpha$, and subset $S \subset L_\beta$, $(\alpha<\beta)$, how do we define a function $w_{x,S}$: $S \to [0,1]$, which reflects the properties of the priority functions w_y on the levels L_k, $k = \alpha+1, \ldots, \beta$? Specifically, what is the function w: $L_h \to [0,1]$?

In less technical terms, this can be paraphrased thus:

Given a social (or economic) system with a major objective b, and the set L_h of basic activities, such that the system can be modelled as a hierarchy with largest element b *and lowest level* L_h. *What are* the priorities of the elements of L_h with respect to b?

Remark H: We assume that the elements in each level may belong to more than a single hierarchy. To measure their priority they must be regarded as <u>independent</u> within a given hierarchy.

From the standpoint of optimization, to allocate a resource among the elements any interdependence must also be considered. Analytically, interdependence may take the form of input-output relations such as, for example, the interflow of products between industries. A high priority industry may depend on flow of material from a low priority industry. In an

optimization framework, the priority of the elements enables one to define the objective function to be maximized, and other hierarchies supply information regarding constraints, e.g., input-output relations.

We shall now present our method to solve the Basic Problem. Assume that $Y = \{y_1, \ldots, y_{m_k}\} \in L_k$ and that $X = \{x_1, \ldots, x_{m_{k+1}}\} \in L_{k+1}$ (*observe, that according to the remark following definition 5, we may assume that* $Y = L_k$). Also assume that there is an element $z \in L_{k-1}$, such that $Y \subset z^-$. Then we consider the priority functions

$$w_z: Y \to [0,1] \quad \text{and} \quad w_y: X \to [0,1] \quad j = 1, \ldots, m_k.$$

We construct the "priority function of the elements in Y with respect to z," denoted w , w: Y→[0,1], by

$$w(x_i) = \sum_{j=1}^{m_k} w_{y_j}(x_i) w_z(y_j) \ , \ i = 1, \ldots, m_{k+1}$$

It is obvious that this is no more than the process of weighting the influence of the element y_j on the priority of x_i by multiplying it with the importance of y_i with respect to z.

As we saw in example 1, the algorithms involved will be simplified if one combines the $w_{y_j}(x_i)$ into a matrix B by setting $b_{ij} = w_{y_j}(x_i)$. If we further set $w_i = w(x_i)$ and $w'_j = w_z(y_j)$, then the above formula becomes

$$w_i = \sum_{j=1}^{m_k} b_{ij} w'_j \quad i = 1, \ldots, m_{k+1}$$

Thus we may speak of the priority vector w and, indeed, of the priority matrix B; this gives the final formulation

$$w = Bw'$$

The following is easy to prove:

Theorem 1: Let H be a complete hierarchy with largest element b and h levels. Let B_k be the priority matrix of the k-th level, k = 1, ..., h. If w' is the priority vector of the p-th level with respect to some element z in the (p-1)st level, then the priority vector w of the q-th level (p<q) with respect to z is given by

$$w = B_q B_{q-1} \cdots B_{p+1} w'$$

Thus the priority vector of the lowest level with respect to the element b is given by:

$$w = B_h B_{h-1} \cdots B_2 w'$$

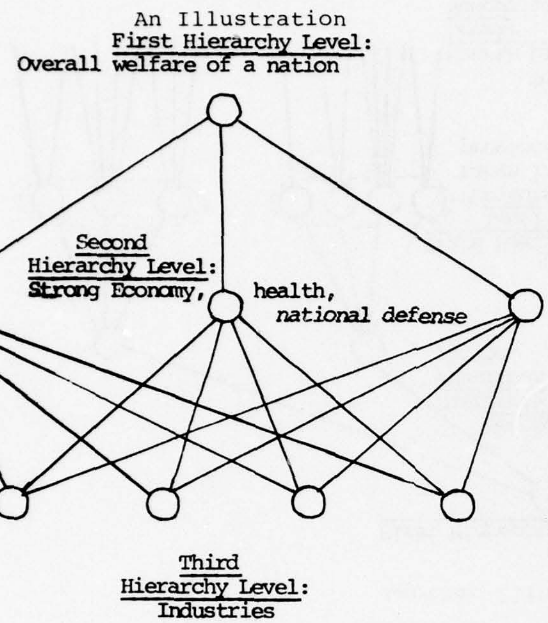
The following observation holds for a complete hierarchy--but it is also useful in general. The priority of an element in a level is the sum of its priorities in each of the subsets to which it belongs, each weighted by the fraction of elements of the level which belong to that subset and by the priority of that subset. The resulting set of priorities of the elements in the level is then normalized by dividing by its sum. The priority of a subset in a level is equal to the priority of the dominating element in the next level.

The following two figures are illustrations of hierarchies used in applications.

FIGURE 1

A TREE OF PRIORITIZATION

An Illustration



First hierarchy level has a single objective used as a criterion below. Its priority value is assumed to equal unity.

Second hierarchy level objectives have priorities derived from their matrix of comparison of their impact on the objejive given in the first level.

Third hierarchy level objectives derive their priorities from their comparison matrix with respect to each objective of the second level and then to obtain the overall priority of each objective, a weighted sum of the priorities is taken using the priorities of the second level objectives as weights.

FIGURE 2

A TREE OF PRIORITIZATION

Another Illustration

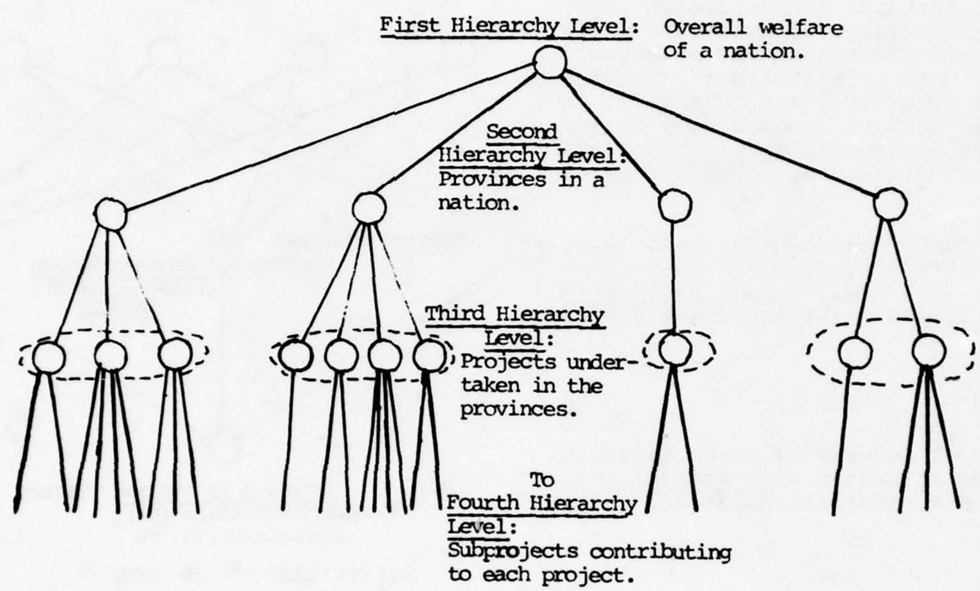


Figure 2 (continued)

First hierarchy level has a single objective as a criterion below. Its priority value is assumed to equal unity.

Second hierarchy level objectives have priority derived from their matrix of comparison of their impact on the objective given in the first level.

Third hierarchy level objectives fall in group according to which element of the second hierarchy they contribute. Their overall priority is obtained from the matrix of comparison of their impact on the relevant objective of the second level multiplied by n_i/m (the fraction of elements in their group indicated by dotted lines with $\sum_i n_i = m$ where i is the index of groupings) and by the priority of the element from the second level class they fall under. Sum of the priorities in each level must add up to unity. This is done by a normalization process of dividing the priority of each objective by the sum of all priorities in the level.

Lower hierarchy level priorities are similar derived based on the immediately preceding level.

Examples. We shall be satisfied here with elementary examples to illustrate the main ideas and perhaps also heighten the interest of the reader in some potential areas to which they can be applied. These examples can be subjected to variations in the structure to test for sensitivity. It turns out that the results are not sensitive to changing the number of elements by a few and even to perturbations in the number of levels. The reader will undoubtedly discern the generality of the method. By applying it he will experience its power to produce answers which can be validated on the basis of the information available.

Perhaps the most important point to make here, is that this type of ratio scale estimate having been found successful in the physical sciences can be used to evaluate social progress where money or other economic measures are not the only significant indices. We can estimate environmental impacts in terms of the various effects pollutants have including those on health or even happiness, however we may wish to define it. Multi-objective criteria weighting receives an integrated treatment within such a hierarchical framework.

Example 3. Three highschools were analyzed from the standpoint of a candidate according to their desirability. Six characteristics were selected for the comparison. They are: learning, friends, school life, vocational training, college preparation and music classes. The pairwise judgment matrices were as follows:

Overall Satisfaction with School

	Learning	Friends	School Life	Vocational Training	College Preparation	Music Classes
Learning	1	4	3	1	3	4
Friends	1/4	1	7	3	1/5	1
School Life	1/3	1/7	1	1/3	1/5	1/6
Vocational Training	1	1/3	5	1	1	1/3
College Preparation	1/3	5	5	1	1	3
Music Classes	1/4	1	6	3	1/3	1

Comparison of Schools with Respect to the Six Characteristics

Learning

	A	B	C
A	1	1/3	1/2
B	3	1	3
C	2	1/3	1

Friends

	A	B	C
A	1	1	1
B	1	1	1
C	1	1	1

School Life

	A	B	C
A	1	5	1
B	1/5	1	1/5
C	1	5	1

Vocational Training	A	B	C
A	1	9	7
B	1/9	1	1/5
C	1/7	5	1

College Preparation	A	B	C
A	1	1/2	1
B	2	1	2
C	1	1/2	1

Music Classes	A	B	C
A	1	6	4
B	1/6	1	1/3
C	1/4	3	1

The eigenvector of the first matrix is given by:

(.32, .14, .04, .13, .24, .14)

and its corresponding eigenvalue is $\lambda = 7.49$ which is slightly far from the consistent value 6.

The eigenvalues and eigenvectors of the other six matrices are:

$\lambda = 3.05$ $\lambda = 3$ $\lambda \approx 3$ $\lambda = 3.21$ $\lambda = 3.00$ $\lambda = 3.05$

Choosing School Problem

Learning	Friends	School Life	Vocational Training
.16	.33	.45	.77
.59	.33	.09	.05
.25	.33	.46	.17

College Preparation	Music
.25	.69
.50	.09
.25	.22

To obtain the overall ranking of the schools, we multiply the matrix whose columns are these vectors on the right by the transpose of the vector of weights of the characteristics. This yields:

A = .37; B = .38; C = .25

The individual went to school A because it had almost the same rank as school B, and he wanted to go there.

He had been going to school B before the analysis was made.

Example 4. The hierarchical method of prioritization may be used to provide insight into psychological problem areas in the following manner:

Consider an individual's overall wellbeing as the single top level entry in a hierarchy. Conceivably this level is primarily affected by childhood, adolescent and adult experiences. Factors in growth and maturity which impinge upon wellbeing may be the influences of the father and the mother separately as well as their influences together as parents; the socio-economic background; sibling relationships; one peer group; schooling; religious status and so on.

The factors above, which comprise the second level in our hierarchy, are further affected by criteria pertinent to each. For example, the influence of the father may be broken down to include his temperament, strictness, care and affection. Sibling relationships can be further characterized by the number, age differential and sexes of siblings; peer pressure and role modeling provide a still clearer picture of the effects of friends, schooling, teachers.

As an alternative framework of description for the second level, we might include self-respect, security, adaptability to new people and new circumstances and so on influencing or as influenced by the elements above.

A more complete setting for a psychological history might include several hundreds of elements at each level, chosen by trained individuals, and placed in such a way as to derive the maximum understanding of the subject in question.

Here we will consider a highly restricted form of the above, where the individual in question feels his self confidence has been severely undermined and his social adjustments impaired by a restrictive situation during childhood. He is questioned about his childhood experiences only, and asked to relate the following elements pairwise, on each level:

Level I	Overall Wellbeing (O.W.)
Level II	Self-respect, Sense of Security, Ability to adapt to others (R,S,A)
Level III	Visible affection shown for subject, (V) Ideas of Strictness, Ethics, (E) Actual disciplining of child,(D) Emphasis on personal adjustment with others (O)
Level IV	Influence of the Mother, Father, Both (M,F,B)

The replies in matrix form were as follows:

O.W.

	R	S	A
R	1	6	4
S	1/6	1	3
A	1/4	1/3	1

R

	V	E	D	O
V	1	6	6	3
E	$\frac{1}{6}$	1	4	3
D	$\frac{1}{6}$	¼	1	½
O	$\frac{1}{3}$	$\frac{1}{3}$	2	1

S

	V	E	D	O
V	1	6	6	3
E	$\frac{1}{6}$	1	4	3
D	$\frac{1}{6}$	¼	1	½
O	$\frac{1}{3}$	$\frac{1}{3}$	2	1

A

	V	E	D	O
V	1	$\frac{1}{5}$	$\frac{1}{3}$	1
E	5	1	4	$\frac{1}{5}$
D	3	¼	1	½
O	1	5	4	1

V	M	F	B
M	1	9	4
F	$\frac{1}{9}$	1	8
B	¼	$\frac{1}{3}$	1

E	M	F	B
M	1	1	1
F	1	1	1
B	1	1	1

D	M	F	B
M	1	9	6
F	$\frac{1}{4}$	1	¼
B	$\frac{1}{6}$	4	1

O	M	F	B
M	1	5	5
F	$\frac{1}{5}$	1	$\frac{1}{3}$
B	$\frac{1}{5}$	3	1

The eigenvector of the first matrix, a, is given by

	O.W.
R	.701
S	.193
A	.106

The matrix, b, of eigenvectors of the second row of matrices is given by

	R	S	A
V	.604	.604	.127
E	.213	.213	.281
D	.064	.064	.120
O	*.119*	*.119*	*.463*

The matrix, c, of eigenvectors of the third row of matrices is given by

	V	E	D	O
M	.721	.333	.713	.701
F	.210	.333	.061	.097
B	.069	.333	.176	.202

The final composite vector of influence on well-being obtained from the product cba is given by

Mother	.635
Father	.209
Both	.156

The subject demonstrates that the input of the mother in terms of the elements considered here far outweighs the father's effect in childhood. Interpretations obviously vary. An improper parental balance rather than a restrictive situation is indicated. In any case the method is extremely versatile for interpreting situations and locating problem sources such as determining the relative strengths of the parents.

5.0 *Concluding Remarks*. We have undertaken comparisons of the eigenvalue approach to measurement with the methods of S.S. Stevens and with the method of least squares as two of the most important methods one may be inclined to use in deriving a ratio scale. First, neither of these methods is implicitly concerned in its derivation with the important measure of consistency as does the eigenvalue approach. The eigenvalue approach, as the least square method, relies on the use of redundant information to improve precision. Both latter methods are based on perturbation equations which arise in estimating ratios in pairwise comparisons. Unlike the more general parameterization in the eigenvalue approach, least square approximation degenerates to the same set of assumptions with or without consistency. Minimizing squares is convenient but is not a process intrinsic to scale derivation any more than minimizing the fourth power would be. However, when it is known that we have near consistency, a least squares solution is a good approximation to the eigenvalue problem. Comparison with the method of S.S. Stevens by having judges locate their relative preferences of the items being compared on a line segment of prescribed length produced less precision for the latter method as the method does not provide a

systematic way of improving overall consistency by using redundant information. Stevens' power law does not seem to be an essential part of the eigenvalue solution.

Hierarchic use of the eigenvalue method yields results on a unidimensional scale. The practical usefulness of such a scale is considerable. For it to be useful, it must yield answers in conformity with logic. But this can be expected from the method of weighting used to derive the scale.

The power relation itself may be reflected in the scale used for making the pairwise comparisons. But in all the examples considered there does not seem to be any reason to conclude, by comparing the matrix of estimated values (a_{ij}) with the matrix of ratios (w_i/w_j) that $a_{ij} = (w_i/w_j)^{\alpha}$. This observation applies both to prothetic (quantitative in nature) and metathetic (qualitative in nature) data discussed by S.S. Stevens. Experiments are under way by a psychologist to compare the two methods using heat lamps to shine light on subjects' upper back part.

The following is a general summary of the steps of a prioritization process within a hierarchical framework.

PRIORITIZATION PROCESS

Step 1	Step 2	Step 3	Step 4
Define and Develop Hierarchical Structure of Levels	Construct Pairwise Reciprocal Matrices to Represent Independence Matrices	Solve for Eigenvectors and Derive some Priority Vectors by Normalization	Test for Consistency and Revise Step (2) to Improve Ordinal Consistency
L_1	$A_1 = (1)$	$w_1 = (1)$	
L_2	A_2	w_2	
L_3	$A_{31}, \ldots, A_{3m_2}$	$w_{31}, \ldots, w_{3m_2}$	
. . .			
L_h	$A_{h1}, \ldots, A_{hm_{h-1}}$	$w_{h1}, \ldots, w_{hm_{h-1}}$	

PRIORITIZATION PROCESS (Continued)

Step 5	Step 6
Form the Priority Matrices	Compute Weighted Products
$B_1 = (1)$	
$B_2 = w_2$	
B_3	
	$w = B_q B_{q-1} \dots B_{p+1} w'$
B_h	

Step 7

Applications

a) Allocate resources in proportion to priorities if complete independence holds.

b) For cost benefit analysis divide the priorities by the corresponding costs and rank the activities accordingly.

c) Solve an optimization problem using priorities as coefficients of objective function subject to interdependence or input-output constraints.

d) Construct social constraints (research in progress) using hierarchical method of prioritization. Solve optimization problem as in c) subject to these constraints.

Thus, after systematically structuring a system into a hierarchy, the eigenvalue method is used to study the laws of interaction between its levels and by superposition, the impact of any level on the overall hierarchy may be obtained through the composite vector for that level. *This provides a method for* studying a fundamental problem in systems theory--the effect of the parts of a system on the whole.

The research is being extended to another type of hierarchy with feedback called a holarchy and to a system that is represented as a network. The question of the stability of a hierarchy to perturbations in its elements and levels is also being researched. A detailed paper with theorems justifying the approach exists.

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REMARKS ON THE PRESENTATION GIVEN BY THOMAS L. SAATY FROM THE UNIVERSITY OF MICHIGAN

by CLYDE H. COOMBS
University of Michigan

Dr. Saaty's approach to a complex decision problem is an instance of a general procedure called multiattribute utility theory which is the most widely used model today and, indeed, it quite dominates the field. Dr. Homan's paper yesterday provided a good example of this model used to aid decision making for a naval force commander. The popularity of the model is such that one attacks it with some trepidation - except that some of the foremost proponents of the model don't believe people behave that way but they like it because it is a good prescriptive model and insines some rationality.

Criticisms and questions raised about what Dr. Saaty talked about may equally well be raised about the mulattribute utility and maximum expected utility.

What the model does in brief is to cut an option up into pieces, its facets or components, assign utilities or values to each facet, reflecting their desirability, with weights or probabilities reflecting their importance or likelihood of occurrence, and then aggregates them into a total value, the expected utility, for each option as a whole, and then choose by maximizing.

What Dr. Saaty has contributed is a new and cleaver way of estimating the utilities to be associated with the various components of an option.

Tom's talk this morning was very interesting and the results intuitively compelling. From the point of view of modelling it is not enough, however, to do a study in which the model fits significantly.

One wants to know if one can do an experiment in which the model will not fit and then what are the characteristics of such

experiments.

In other words what are the conditions that characterize the model, that control its degree of fit.

This model makes certain assumptions which must be satisfied for accurate results. The component factors must be a mutually independent and eshaustive list and combine additively without the values interacting with their weights or probabilities.

These characteristics of the method are well-known but are not easy to satisfy. Another assumption of the model reflects the fact that the decomposition of an option into all its disjoint components may not be unique-and that requirement is that the aggregate value of an option must be invariant over all possible such decompositions.

The model is designed to play the role of the decision maker, the commander. I like the attitude expressed by Dr. Wagner that a model should provide insights, of a qualitative nature, and point directions. I presume that what he has in mind is that the model must be an aid to the commander but leave the ultimate decision up to him, for reasons which I will try to spell out shortly.

Maximum expected utility is a model in which the commander would only be used to assess utilities and weights or probabilities and then it will put them all together. When the conditions for the model are not satisfied it may come up with an answer which is then rejected. I am reminded here of a study made at the behest of the Mexican government to determine the best location for a new International airport for Mexico City. Specialists and experts in Mexico City were used to estimate values and costs for demographic factors, pollution factors, economic, social and physical factors. The solution the model arrived at was rejected by the City fathers for essentially political reasons which were not adequately represented in the decomposition.

However, one of the great values of this model, this approach to the decision problem, is that it leads, in fact, forces, the decision maker to examine each of his options in terms of all its facets, its bits and pieces in detail, to penetrate the problem to a greater depth than he is likely to in the absence of the model.

A major reservation I have about this approach is that the options are invariably risky ones and it has surprised me that the notion of risk and risk-taking has so little entered into the discussion. General Welch mentioned it in his talk and so did Dr. Homan yesterday morning and Mr. Robinson in the afternoon when he referred to rash and cautious commanders. These references, however, were casual and passing, and I think that the reason for this is that utility theory preempts the concept of risk, it is redundant.

In the von Neuman axioms for measure utility, for example, a risky proposition is put up versus a sure thing and if the individual does not maximize expected value when he indicates his choice, then the utility function is shaped to explain his behavior as maximizing expected utility - there is nothing left over for a notion of risk. Unfortunately it can be shown without much difficulty that maximum expected utility is incorrect as a descriptive theory.

It seems to me that the notion of risk is a significant psychological variable in the options a commander faces. The efficient options consist of options in which the risk is minimal for the gain to be expected and the gain is maximal for the risk undertaken. So the choice then is a matter of the trade off between what more you expect to gain for taking an option with more risk. This parallels the problem of portfolio selection in economic theory. In Mackowitz's theory of Portfolio selection risk is defined in terms of variance and an efficient set of options is determined on the basis of minimizing risk holding expected value constant and maximizing expected value

holding the variance constant. The set of options arrived at are all equivalent by definition. They are not, of course, equivalent from the point of view of human choice. This is an individual matter of trade off between risk and expected value and is an open research problem - both as a descriptive problem and as a normative problem. More risk is justified if the potential gain is great enough - people don't put all their money in government securities.

The problem then becomes one of measurable risk and potential gain and then the commander would decide whether it's worth it given his mission, which puts boundaries on the options available to him.

The problems of measurable risk and potential gain are exacerbrated because they may be different at each echelon of command. Loss of personnel, material, and terrain are perhaps weighted differently at each command level.

I'm not sure that this approach would lead to a more useful model but it does point up risk taking as the only negative variable and the potential gain as the positive one.

All these decision models are simplifications, one might say over-simplifications, and a risk versus gain model is another gross over-simplification but it directs our attention to seeking and interpreting information so as to bear on the estimate of risk and the estimate of gain. Then the trade off is the commander's decision.

One of the things I would worry about in an expected utility model is that if the enemy knows your utilities you are predictable and hence more vulnerable. A training program which leads to too great uniformity of utilities and decision criteria could be self-defeating.

In a risk-theoretic approach the same situation in terms of outcomes and probabilities would still leave the cause of action unpredictable because it is dependent upon the commanders trade off between risk and gain.

Let me make a few remarks stimulated by Dr. James Miller's talk. Jim's paper was on a very general level which is an approach that has wide applicability but correspondingly less power. It doesn't say very much but it says it about a vast number of things. This is in contrast to a more specific model which has greater power, which says a great deal more but about a lot less. Jim has exercised analogical reasoning by using all living systems as analogies for each other and has abstracted their universal properties and processes. The value of the approach lies in leading one or guiding one through a more thorough analysis of any one system and not missing any major aspect.

I guess my point is that the entire spectrum from very general to very specific models is correspondingly a spectrum from weak to strong models that this is correlated with being long-lived or short-lived (the more specific the model the more it will do for you when its applicable, the fewer things it is applicable to, and the shorter its half-life) and my point is that research at any level in this spectrum is valuable.

REMARKS ON THE PRESENTATION ENTITLED
"INTERACTION AND IMPACTS IN HIERARCHICAL SYSTEMS"
GIVEN BY T. SAATY, UNIVERSITY OF MICHIGAN

by ANGELO MIELE
Rice University

First of all, I would like to compliment Professor Saaty for an excellent presentation of his approach to hierarchies. His approach is of considerable interest to me, since it might have potential interest in the development of algorithms for mathematical programming problems with inequality constraints.

Nevertheless, a key point needs clarification. In performing numerical pairwise comparisons between complex activities, priorities are assigned (in accordance with our feelings and experience) while using the sequence of cardinal numbers

$$\{ 1,2,3,4,5. \ldots\ldots\ldots \} \tag{1}$$

Any subsequent result in Dr. Saaty's presentation seems to be a direct consequence of the basic assumption (1).

Now, suppose that priorities are assigned using some alternative sequence, for example:

$$\{ 1^2,2^2,3^2,4^2,5^2, \ldots\ldots \} , \tag{2}$$

or

$$\{ 1^3,2^3,3^3,4^3,5^3, \ldots\ldots \} , \tag{3}$$

or

$$\{ \sqrt{1},\sqrt{2},\sqrt{3},\sqrt{4},\sqrt{5}, \ldots\ldots \} , \tag{4}$$

or

$$\{ 1, 1+k, 1+2k, 1+3k, 1+4k, \ldots\ldots \} , \tag{5}$$

where k is some positive number, for instance,

$$k = 0.5 \quad \text{or} \quad k = 2. \tag{6}$$

It is obvious that the replacement of (1) with any one of the sequences (2), (3), (4), or (5) would cause a change in the conclusions arrived at by Dr. Saaty. Therefore, it is natural to pose the following question: what is the sensitivity of the results obtained to a change in the sequence of numbers employed in the assignment of priorities? How critically do the results obtained depend on the choice of the particular sequence (1)? Since this point is crucial to Dr. Saaty's presentation, his views on the subject would be appreciated.

REMARKS ON THE PRESENTATION GIVEN BY C. H. COOMBS,
UNIVERSITY OF MICHIGAN

by ANGELO MIELE
Rice University

I would like to state my agreement with the views expressed by Professor Coombs on the nature of scientific research. After a theory has been developed on any given subject, it is nice for any of us to perform experiments confirming the theory. Obviously, this is good for our ego. However, scientifically speaking, it is even more important to perform those experiments which might invalidate some aspects of the theory or might lead to the discovery of some weakness in the theory. Only in this way can one hope to advance the frontiers of research.

As scientists, we have an obligation to ourselves not to let wishful thinking submerge our cool professional judgment. Also, we have an obligation toward the scientific community to stress both the good points and the bad points in our research. Finally, we have an obligation to the government agencies that support our work to state the facts as they are.

The philosophy expressed by Dr. Coombs has been precisely my philosophy for a long time. Over the past ten years, my work at Rice University has been concerned primarily with the development of algorithms for all sorts of problems of applied mathematics. My basic viewpoint has been that of testing exhaustively these algorithms in order to discover possible weakness and either (i) takes steps to correct these weaknesses or (ii) state clearly these weaknesses so that they could be corrected in subsequent work.

As an example of this point of view, I would like to mention the following. At Rice University, one recent algorithm for mathematical programming problems was tested through 29 different

numerical examples, including many examples of the so-called pathological type. By generating exceptional numerical difficulties, we were able to arrive at needed corrections which increased in a drastic way the so-called robustness of the algorithm, namely, the ability of the algorithm to solve the problem being considered under a wide variety of operating conditions.

DISCUSSION

The foregoing paper was the theme of a keynote address. The discussion of that address was short and is given below. It is then followed by a summary of a second talk and a discussion.

Lehman: After 26 years with the Air Force I have come to the enlightenment that I am a bureaucrat - but with this process you can come up with answers to the unanswerable problems. Eight years ago the Air Force went through an exercise which one tenth dubbed an absolute stupidity called TORK. The name of the game was called "Hey figure out what the Air Force should be doing: what are the important missions it ought to be under taking and give a weighting to these ventures. He called these things OCO - Operational Capabilities Objectives, and you honor the rating system such as if you said Strategic offensive was number 1 and you gave it a weighting of 95 and you know Air superiority was number 3 and you gave it a weighting of 62 and you gave Air rescue and Air superiority and the number was less that strategic offensive, you lost strategic offensive before you did the other two. Well you can imagine when we three this to doctorines and concepts, they struggled valiantly with it for six months. They finally got down 19 categories that they would divide the world into and they could come to absolutely no agreements on the numbers. Except they had to give an answer so they threw an answer out and this answer was sent down with the statement - "for the purposes of computing how we will get out budget for 6.2 we can regard this as an exercise". What you've come up with here is the answer.

Saaty: The idea is not that we get the universal answer but that we find out why we think the way we do, why we have the judgments we have or why we get different answers. We don't want the world to consist of people who all think alike, except maybe when important decisions need majority support. We want a way of identifying people and trying to see if we can get them in a bargaining process so they might change their point of view.

The author gave another paper which was an application of the theory to planning. The hierarchy consists of the following levels: The first or highest level is the projected future of higher education in the U.S. in 1985. The second level consists of the forces which shape that future: economic, social, political and technological. Following it is a third level of the actors who manipulate the forces by pursuing their objectives. They were: students, faculty, administration, government, industry and private institutions who contribute to higher education. Each of these actors has a set of objectives which were listed on a fourth level. The fifth level of the hierarchy is occupied by a set of seven potential outcomes of higher education; e.g., the status quo (present trends) extended to 1985, elitism, putlic education for all, government owned institutions, etc. The outcomes or scenarios were characterized by a set of twenty-five state variables whose values were calibrated on a scale from -5 to 5 as they differed from their present value, zero, taken as the reference point. Now the eigenvalue method was applied to the hierarchy resulting in a composite vector for the scenarios. Linear (in fact convex) combinations of the values of each state variable over the scenarios were formed using the weights of the scenarios as coefficients. The resulting values of the state variables characterized what is known as the composite scenario, the trend of the future that is the resultant of all the forces. This method of approach to planning involves an analysis of the beliefs of the participants. (There were 34 people, all educators, who debated their judgments over a period of about 12 hours). It is known as the <u>forward planning process</u>. Another important aspect of planning is the <u>backward process</u> (concerned with the values of the participants) which begins with an idealized future and strives to find policies for actors to influence other actors and surmount obstacles to attain that future. These policies may be incorporated as a new level under the objectives of the actors in the forward process and a new composite future derived to test the

effectiveness of the policies thus developed. Together the forward and backward processes define a two-point boundary value planning problem. Iteration of the two processes leads to a more realistic assessment of the interface between beliefs and values. The numbers obtained were very reasonable and the participants were encouraged to find that there would be changes in higher education but there is no disaster in sight in any of the variables considered. The paper is appearing in the Journal of Socio-Economic Planning, December 1976. The following discussion refers to both papers.

Question: As I understand it, what you're doing, is, you've got an amorphous mass of data from asking these questions and this is an attempt to give it structure. Not give it structure, but to quantize.

Saaty: Yes. the numbers are supposed to reflect the structure.

Question: But really how do you have dynamics in this model?

Saaty: By constructing the problem and providing judgments to cover more than a single period of time. The solution vector will then be a function of time.

Question: Suppose I believe all your numbers. Suppose that I agree that all these forces are at play. When are they going to have the degree of effect that you indicate?

Saaty: The method can only measure what people believe. If they are known to be good interpreters of reality, then results should reflect that understanding of the real world.

Question: I thought you might respond to a couple of questions from a different point of view. One question is, where is the model of the process that is going on? One thing we noticed when we were looking at decision aids for ONR was that there were really two quite different types of models that people use or find useful. One is where the model of the process itself is in the computer or in the overt procedures. The other is where the model is really in people's heads. The procedure that you are using is a way of organizing or systematically collecting in order

to get a consensus of the group which is better than they could produce without the organizing procedure. It seems that what you are doing is an organizing procedure which is exploiting the models of the process which are really in people's heads.

Question: Do you apply the same kind of procedure to determine when the trend you determine is going to have its effect?

Saaty: How effective plans turn out depends on many factors which, if represented in the hierarchy, yield an opportunity to test sensitivity and find out where to put one's greatest efforts to bring about a desired outcome.

Question: On Thursday, you applied it to your son's choice of school. You seemed to be satisfied that he had an adequate grasp of what he really was happy or unhappy about. Was the model used in your decision, or was that just an exercise?

Saaty: Yes. The son was taken out of that school as a consequence of the model. My wife who participated in the exercise and had preferred school B, was also convinced of the result. A student of mine who had finished his work chose his job by a similar approach. When his boss quit that working place, a factor which he hadn't considered in his hierarchy, he went to work at the second choice job.

Question: I was wondering what your definitions of the lambda's were in the consistency test. You had lambda max - n over n on the board. Was that what these lambda's were?

Saaty: The lambda's are an indication of how consistent the numerical data are. If lambda max - n turns out to be large then what you have to do is revise the judgments by greater familiarity with the problem which can involve delays to learn more about it. One way to test how good the data are is to compare this index with its average value from matrices of the same order whose entries are randomly chosen from the scale 1-9.

Question: You had a perfect one on there once, in the two dimensional case. The two dimensional case always has to be perfect.

Saaty: It always has to be consistent.

we are looking for the independence properties. However, there is also a way in which one can include dependence in a way similar to generating input-output relations. What one does is to use for the criteria or properties each one of the activities themselves. And then one measures how activity A compares with activity B as far as the functioning or productivity of each one of them is concerned. This leads to a matrix of pairwise comparisons whose eigenvector yields a measure of the dependence of one industry on all others. In this manner we obtain a matrix of eigenvectors. It can be weighted by the "independence" priority vector of the industries to obtain a joint interdependence vector - the one you are looking for.

Question: Have you had the opportunity to work this hierarchical exercise as you did with the educators with two different groups of people in the same business to see what sort of consistency of projections you get? What are the results?

Saaty: Of course, even having only one audience of independently minded people who carry out a heated debate over their judgments is a good enough example. Each participant attempts to influence the outcome according to his strength with the group. A very strong minded individual can dominate the group and bias the outcome in his favor. The audience must be alerted openly to this possibility. If individuals conduct the process separately, one may obtain consensus by averaging over their resulting solutions. However, group participation is best when none of the people is an expert.

Question: It seems to me this might be a way to rationalize the requirements generation process which is sometimes, in the aggregate, not a very rational process.

Miele: If my understanding is correct, you are comparing a certain number of items from the point of view of certain categories of things that you have recorded. From the lecture of the other day, I remember that you used a system of cardinal numbers to order the relative importance of the things. Obviously, this was

a kind of arbitrary assumption. Suppose I order the relative importance of the things in a different way? Suppose I say I don't want to use the number 1, 2, 3 but rather the squares or cubes of these numbers. How sensitive is the answer you get to this basic assumption?

Saaty: In fact, the other day I failed to tell you that the most fascinating thing about this is that these numbers are cardinal numbers. I showed that if you put cardinal ratios in the matrix, you recover the scale by solving the eigenvalue problem. Then I said that when people provide judgments, they will usually get inconsistencies around these numbers. I wanted an aggregate measure of how well they are doing. The expert will give me a lambda max near to n. Presumably, the inexpert will have larger deviations. So what we are doing is to obtain estimates of an underlying ratio scale. The scale 1-9 has been tested in a variety of examples against 25 other scales, in matrices whose entries were given qualitatively according to the scale. It yields a better representation of the underlying scale using root mean square, median absolute deviation about the median as measures than the other scales.

Welch: Wherever you have 1, 2, 3, 4, replace those by another set of numbers that are still ordered by make a one to one substitution. What happens to the mathematics?

Saaty: You don't get as good an answer. In fact, for most substitutions you will get an unsatisfactory estimate of the underlying scale.

Welch: But have you ever tried, say, 1, 1.1, 1.2? What happens then?

Saaty: What would be desirable would be that both the numbers and their reciprocals be far enough apart so that they would be a true representation of your feelings. We have error here. If we make an error in judgment, we don't want to mix that with distinguishing between one judgment and the next one. I tried $1+\varepsilon$ and $1/(1+\varepsilon)$. It seems to me that you cannot distinguish between $1+\varepsilon$ and $1/(1+\varepsilon)$

very well. In other words, the property and its inverse would be about the same. You have to separate them adequately.

Welch: I was trying to separate the question between the judgments. I'm perfectly happy to do it that way. Then just crank through the mathematics of the different scales.

Thrall: It's clear that if you took the numbers 1, 2, 3, 4 and then the next ones were 51, 52, 53, 54, you can start to see the problems. I think this is pretty obvious. You are going to weigh everything in terms of those other tings and the first ones are going to count like zero. But if you had 1, 3, 5, 7, instead of 1, 2, 3, 4, that probably wouldn't make any vast difference. The question you ask is really one that hasn't been investigated.

Saaty: Let me tell you why, for example, 1 to 100 doesn't work well. When people have many numbers to choose from, they start changing their minds by several integers on the lower end of the scale. To go from 3 to a 7 on a 1 to 100 scale means that one is changing one's judgment of the strength of dominance by 7/3 or 2-1/3. Going from 40 to 50 implies a change of 5/4 although it involved adding 10 points. The scale offers great opportunity for biasing the results.

Question: I would like to suggest a very simple answer to all of this. Out of the simple cardinal numbers from 1 to 7 and their combinations and fractions, you can build up a ratio from 7 to 1 and 1 to 7, and almost anything in between with increments which are appropriate to human judgment. If you go to much larger numbers, you get much smaller increments and nobody can judge that finely. It gives you a sufficient feel to express feelings. Any time you are not consistent in the choosing of the relative weights, in each of your rows, you will get an inconsistency. And the aggregate of that is reflected in increase of lambda over N. If you are perfect in your judgments and the expressions of your judgments, you will always have lambda equal N.

Question: I would like to make the observation that independent of the numbers and the method you are going. I am reminded that

at the Philadelphia ORSA meeting there were several papers directed at recovering structure from this kind of data. One asked people to draw a map of South America based on how far away they remembered Argentina was from Chile and so on. You have a method here. It appears that what the way you could use this, independent of the method you chose, was to ask people to construct a command and control network as they perceive it. They compare that with the physical command and control network that actually exists. Try to uncover what it is that is causing this disquiet about whether it works or doesn't.

Question: Another comment about the scaling of the numbers. Don't forget that the purpose of all this is do disambiguate our own thinking where our own ability to project is somewhat fuzzy. If it becomes clear that our factor is 100 times more important than another, then that becomes an assumption. That doesn't go into the table at all. Where Dr. Saaty's techniques seem to have relevance is in the fuzzy in between area. It is reasonable that the numbers are in a fairly narrow range.

SOME STATISTICAL PROBLEMS IN LOGISTICS RESEARCH
AND MILITARY DECISION PROCESSES*

by S. ZACKS
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Abstract. The present paper discusses some problems of large systems logistics and tactical decision processes which require the development of proper statistical theories and methods. The discussion is focused on three problem areas: statistical control of two-echelon multi-station inventory systems; statistical manpower forecasting and survival distributions in crossing mine fields. The discussion is general but specific numerical examples are provided to illustrate the ideas.

1.0 Introduction. Logistics research covers many different areas related to problems of designing and controlling large dynamical systems. In recently published books [3, 6] one can find several good discussions of these problem areas and the modern trends in logistics research. This research is carried for the purpose of developing efficient management procedures of the total support functions of large systems. We include today among these functions not only the traditional ones, namely: design of facilities; production planning and control, assignment and allocation problems, inventory control, transportation and others but also problems areas concerned with the reliability and maintainability of weapon systems; tactical mini- and maxi-combat problems, etc. In all the areas mentioned above statistical research occupies a

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central position. One can find hundreds of papers that have been written on various stochastic and deterministic optimization methods in each one of the areas mentioned above. Not much is available, however, in the literature on statistical theories and methods. This is partly due to the complexity of the problems and partly to the widespread practice of applying the established "optimal" procedures in which simple estimates of the unknown parameters are substituted. In many cases such a simple approach yields adequate results. It cannot, however, be always recommended, as will be discussed later.

The objective of the present paper is to expose and discuss some statistical problems, which the author has studied in the past, and to indicate fruitful problem areas for further research. In our exposition we will discuss the following problems:

1) Statistical control of two-echelon multi-station inventory systems;
2) Adaptive manpower forecasting model;
3) Strategies of crossing mine-fields.

These problem areas are not the only interesting ones. There are other interesting statistical problems in the field of logistics research, like problems of evaluating the readiness of systems, reliability estimation, sequential determination of surveillance epochs and others. For some discussion of these problems see Chapter 10 of Modern Trends In Logistics Research [6].

2.0 Two-Echelon Multi-Station Inventory Problems. In the present section we give an example of a complicated inventory control problem which requires statistical techniques, since the information on the demand distributions is incomplete. The problem we consider is that of determining optimal stock policies in a two-echelon multi-station model, designed for naval applications. The two echelons under consideration are the depot, D (upper) and tender-ships, $T_1,\ldots,T_k$ (lower). The customers

arriving at the stations are submarines. We assume that the monthly demand for a specified item, at station T_j is a random variable X_j, $j = 1,\ldots,k$.

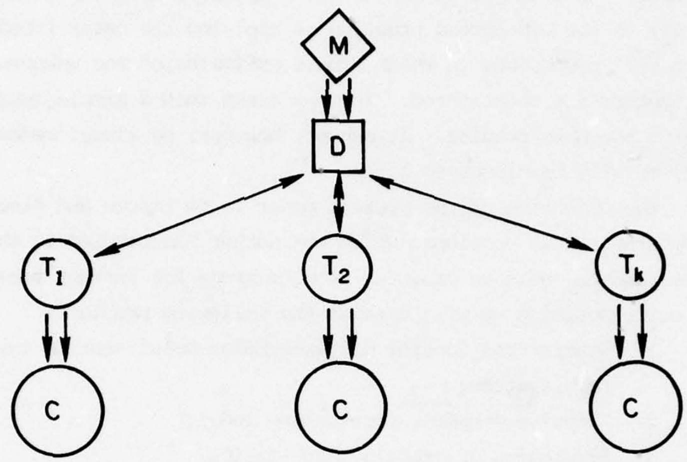

Figure 1. Inventory flow in a two-echelon multi-station model.

The flow of material in the system is described in Figure 1. The stations can order from the depot, D, at the beginning of the n-th month a quantity $Y_{j,n}$, or could send back to the depot unneeded stock. If $Q_{n,j}$ denotes the stock level at T_j at the beginning of the n-th month then $Y_{n,j} \geq -Q_{n,j}$, for all $j = 1,\ldots,k$. Moreover, $\sum_{j=1}^{k} Y^+_{n,j} \leq V_n$, where $Y^+ = \max(0,Y)$ and V_n designates the stock level at the depot at the beginning of the n-th month. The depot orders from the manufactures at the beginning of the n-th month a quantity Z_n, which arrives at the depot only ℓ months later. The lead-time between the upper and the lower echelons is one month. The objective is to determine

at the beginning of each month order levels $(Z_n, Y_{n,1}, \ldots, Y_{n,k})$ so that the expected total lower echelon cost

$$C(\underset{\sim}{Q}_n, \underset{\sim}{X}_n) = \sum_{i=1}^{k} \{c_i(Q_{n,i} - X_{n,i})^+ + p_i(Q_{n,i} - X_{n,i})^-\}$$

will be minimized and the probability that at each month the depot will be able to satisfy the demand of the stations will not be smaller than a preassigned tolerance level γ. Zacks and Fennell [11,12] studied the problem when only partial information on the distributions of the demand variables $X_{n,i}, \ldots, X_{n,k}$ is available. Bayes adaptive control procedures were developed. These procedures determine after every month, according to the total observed demand at each station, the predictive distribution of the future demand variables. The predictive distributions obtained from the Bayesian model are negative binomial with adaptively changing parameters. The negative binomial distributions were previously fitted by Haber and Sitgreaves [4] to the demand for repair parts in the Polaris fleet. Such distributions were also fitted by Denikoff, Fennell, Haber and Solomon [2]. It was shown in these previous studies that the negative binomial distributions, which depend on two parameters, can provide an adequate fit to the demand distributions, which depend on two parameters, can provide an adequate fit to the demand distributions of most classes of items in the submarine fleet. In the Bayesian model, if we assume that demand variables $X_1, X_2 \ldots$, for a certain part, at different months are, conditionally an θ, independent and identically distributed having a Poisson distribution with monthly average θ, and if θ has a prior gamma distribution, $G(\frac{1}{\tau}, \nu)$, then the expected distribution of X_{n+1}, given that $\sum_{i=1}^{n} X_i = T_n$, is the negative binomial distribution with p.d.f.

$$P[X_{n+1} = i \mid \psi_n, \nu_n] = \frac{\Gamma(\nu_n + i)}{\Gamma(i+1)\Gamma(\nu_n)} \psi_n^i (1 - \psi_n)^{\nu_n}, \; i = 0,1,\ldots$$

$$\text{with } \psi_n = \frac{\tau}{1 + (n+1)\tau} \text{ and } \nu_n = \nu + T_n.$$

This distribution is called the predictive distribution of X_{n+1} given the past history of the demand. The model is thus much more flexible, since the predictive distributions applied for the determination of the optimal stock levels are not the same every month, but keep adapting to the actual results. Algorithms for the determination of the optimal order levels at the lower echelon and the upper echelon were developed. For the proof of optimality of the overall procedure see Zacks [8]. The cost function $C(\underset{\sim}{Q}_n, \underset{\sim}{X}_n)$ looks simple enough, but due to the structure of the inventory flow, the determination of the order vector $\underset{\sim}{Y}_n$ should minimize the expectation

$$R(Y_n;Q_n) = \sum_{i=1}^{k} E_{i,n}\{c_i[(Q_{n,i} + Y_{n,i} - X_{n,i})^+ - X_{n+1,i}]^+$$

$$+ p_i[(Q_{n,i} + Y_{n,i} - X_{n,i})^+ - X_{n+1,i}]^-\}.$$

This is the expected cost due to shortage or excessive stock at the end of the (n+1)st month, computed according to the predictive distribution of $X_{n,i}$ and $X_{n+1,i}$, determined at the end of the (n-1)st month. The program for the determination of the optimal $\underset{\sim}{Y}_n$ is not too complicated and the computations are quite fast. On the other hand, the determination of the optimal upper echelon ordering, Z_n, for a lead-time of $\ell = 2$ months requires to find, at the end of the (n-1)st month the smallest integer z which satisfies the inequality

$$P\{z+Z_{n-1}+V_n \geq \sum_{i=1}^{k} (Y_{n,i}+Y_{n+1,i}) + \sum_{i=1}^{k} (k_{n+2,i}-Q_{n+2,i}) \mid \underset{\sim}{T}_{n-1}\} \geq \gamma,$$

where $(k_{n+2,i} - Q_{n+1,i})$ is the desirable ordering level of the *i-th station two months in the future. This conditional prob-*ability, which depends on the total observed demand, T_{n-1}, at all the k stations during first $n-1$ months. is a very complicated predictive distribution. In order to approximate it by simpler predictive distributions we have performed extensive simulations of such systems, with the exact computations of the Z_n values. In the following table we illustrate a Six-Station case where the demand variables at each station are independent Poisson with different means, λ.

Table 1. The parameters of a 6-station system.

i	ν_i	τ_i	Q_i	c_i	p_i	x_i	V	Z
1	19.	2.	0	2.	12.	2.	-	-
2	19.	2.	2	4.	10.	4.	-	-
3	19.	2.	4	6.	8.	6.	-	-
4	19.	2.	6	6.	8.	8.	-	-
5	19.	2.	8	4.	10.	10.	-	-
6	19.	2.	10	2.	12.	12.	-	-
Depot	-	-	-	-	-	-	1	0

Table 2. A 12-months simulation of a 6-station system.

n	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6	Y_1	Y_2	Y_3	Y_4	Y_5	Y_6	V	Z	COST
1	0	2	4	6	8	10	5	0	0	0	0	0	5	62	108
2	0	0	0	1	0	0	0	0	0	0	0	0	0	1	314
3	0	0	0	0	0	0	10	10	7	10	11	14	62	63	94
4	9	6	2	1	0	0	0	0	0	0	0	7	7	12	312
5	9	0	0	0	0	0	0	10	9	10	15	19	63	66	86
6	6	2	0	1	3	4	0	0	0	0	0	12	12	19	252
7	4	0	0	0	0	4	3	10	10	12	15	16	66	68	120
8	5	7	2	4	7	9	0	1	0	3	6	9	19	19	98
9	3	4	0	0	2	14	5	8	13	15	16	8	68	65	202
10	7	9	11	4	10	11	0	0	0	9	5	8	22	21	252
11	6	4	9	5	7	6	2	7	2	10	11	17	65	49	200
12	5	9	0	8	8	17	2	2	12	7	9	5	37	38	156

This table shows that after a few months of correcting a system which is ill conditioned, the system stabilized, and the optimal z_m values are approximately equal to the sum of the Y_n values only for several months. We have also shown in [11] that the Y_n and Z_n values which are determined by using Poisson distributions with estimates of the λ values, yield average monthly cost larger than the ones obtained by the Bayes adaptive procedure. This illustrates well the need for the development of proper statistical procedures.

3.0 Adaptive Manpower Forecasting Models. In the present example we would like to present a forecasting problem which does not belong to the class of problems which are suitable to the commonly used time-series forecasting like those discussed by Box and Jenkins [1]. The problem is that of periodic forecasting of the total size of the Marine Corps, and the size of certain parts of the force. The need for a statistical method of forecasting the size of the force, despite the fact that individuals belonging to the force sign service contracts, is due largely to the problems of random attrition. This attrition is not of constant propor-

tions at every time period and at different units of the force. Withdrawal from service among the career force personnel is of different characteristics than that of first enlistees. The factors which significantly affect the attrition of the first-term enlistees were studied by Haber [4]. It was found that among many different possible factors the ones which significantly influence the retention rates are: length of contract, year of entry to the force, education and race. These factors are not independent; moreover, the year of entry to the force is an important variable because many of other possible factor of apparent theoretical importance (economical, sociological, psychological and political) are actually time dependent. Thus, if we classify the individuals according to the year and quarter of entry, length of contract, education (less than high school, at least high school) and race (white and non-white) all the other factors do not contribute significantly to the improvement of the forecasting. On the other hand, different parts of the career force show high similarity of retention rates. It was found that one retention rate can be used for the whole career force at each forecasting period. The career force rates shows also small variability over time.

The methodology of forecasting applied in our studies is based on the estimation of the retention probabilities of certain subpopulations over the last quarter, and determining prediction (or tolerance) intervals having the characteristic that, with confidence probability ($1-\alpha$) we anticipate the size of the groups under consideration to belong at the end of the next quarter to the intervals. Several methods of determining the prediction intervals were compared.

In the following table we illustrate the prediction intervals determined by three methods (conditional maximum likelihood - CMLE; tolerance limits and Bayes prediction limits) as determined on actual Marine Corps data.

Table 3. Prediction limits for the size of cohorts on July 2, 1972 (= .05). Forecasting on January 1, 1972.

i j k m	CMLE		Tolerance		Bayes		Actual
1 1 1 1	1401.	1434.	1382.	1446.	1393.	1439.	1418.
1 1 2 1	507.	520.	496.	523.	502.	521.	499.
1 2 1 1	3272.	3303.	3253.	3315.	3264.	3307.	3280.
1 2 2 1	676.	693.	665.	697.	671.	694.	674.
2 1 1 1	935.	979.	912.	997.	926.	986.	1009.
2 1 1 2	876.	916.	855.	932.	867.	922.	910.
2 1 1 3	1133.	1165.	1115.	1177.	1125.	1170.	1155.
2 1 2 1	113.	130.	103.	136.	109.	132.	135.
2 1 2 2	98.	111.	89.	114.	94.	112.	104.
2 1 2 3	158.	169.	149.	171.	154.	170.	163.
2 2 1 1	1973.	2009.	1952.	2023.	1964.	2014.	2019.
2 2 1 2	2277.	2309.	2257.	2322.	2269.	2314.	2301.
2 2 1 3	1112.	1133.	1099.	1140.	1106.	1136.	1121.
2 2 2 1	246.	260.	235.	264.	241.	261.	256.
2 2 2 2	223.	236.	214.	239.	219.	237.	230.
2 2 2 3	171.	181.	163.	183.	167.	182.	177.
3 1 1 1	1467.	1518.	1440.	1540.	1456.	1527.	1570.
3 1 1 2	1692.	1749.	1663.	1773.	1630.	1758.	1781.
3 1 1 3	2261.	2325.	2223.	2352.	2247.	2335.	2347.
3 1 1 4	2554.	2616.	2522.	2643.	2541.	2627.	2633.
3 1 1 5	2952.	3001.	2924.	3022.	2940.	3010.	2979.
3 1 2 1	147.	166.	136.	173.	142.	169.	165.
3 1 2 2	167.	187.	156.	194.	162.	190.	190.
3 1 2 3	266.	291.	252.	300.	260.	294.	292.
3 1 2 4	279.	300.	266.	207.	274.	302.	294.
3 1 2 5	391.	404.	380.	403.	386.	405.	386.
3 2 1 1	3333.	3379.	3307.	3399.	3322.	3387.	3403.
3 2 1 2	4623.	4676.	4594.	4699.	4611.	4685.	4675.
3 2 1 3	3380.	3427.	3354.	3447.	3369.	3435.	3416.
3 2 1 4	4115.	4159.	4090.	4177.	4104.	4166.	4108.
3 2 1 5	3207.	3240.	3187.	3252.	3199.	3245.	3207.
3 2 2 1	331.	348.	319.	353.	325.	350.	345.
3 2 2 2	431.	452.	417.	459.	425.	455.	451.
3 2 2 3	411.	432.	397.	440.	405.	435.	428.
3 2 2 4	466.	488.	453.	496.	460.	491.	478.
3 2 2 5	526.	540.	516.	544.	522.	541.	526.
Sums	48170	49249	47537	49656	47902	49404	49130

In the above table, the index i (i=1,2,3) designates the three types of contracts (2,3,4 yrs). The index j (j=1,2) designates the race (W,n-W). The index k (k=1,2) designates the education (LHS,AHS) and the index m designates the time of enter-

ing the force according to the following code:

i	m	Entry
1	1	Jan. 1971
2	1	Jan. 1970
	2	July 1970
	3	Jan. 1971
3	1	Jan. 1969
	2	July 1969
	3	Jan. 1970
	4	July 1970
	5	Jan. 1971

If we denote by $X_{ijkm}(t)$ the size of the (i,j,k,m)-th subpopulation after t periods (of six months) then the basic theoretical model is that, for each such subpopulation the conditional distribution of $X_{ijkm}(t)$ given $X_{ijkm}(t-1)$ is the binomial, $B(X_{ijkm}(t-1), \theta_{ijkm}(t))$; where $\theta_{ijkm}(t)$ is the retention probability for the subpopulation during the t-th period. The CMLE method provides $(1-\alpha)$-prediction intervals for $X_{ijkm}(t)$, given $X_{ijkm}(t-1)$, when the retention probabilities are estimated from the data by the conditional maximum likelihood estimators. *The tolerance limits and the Bayes limits are con*structed by considering first the $2\text{ARCSIN}(\sqrt{\theta})$ transformation;

$$Y_{ijkm}(t) = 2\sin^{-1}\left(\sqrt{\frac{X_{ijkn}(t) + .5}{X_{ijkm}(t-1) + 1}}\right) .$$

This transformation has desirable characteristics in terms of variance stabilization even for medium size samples. We will not provide here the derivations and the formulae of the prediction limits. The interested reader is refered to Zacks and Haber [14]. Total force forecasting procedures were applied by the Marine Corps following the technical paper of Zacks [10]. The method was also applied to a problem of forecasting the retention of Navy pilots.

4.0 Strategies of Crossing Mine Fields. The study on strategies of crossing mine fields was performed in 1963-1966 (see Zacks and Goldfarb [11] and Zacks [8]) and renewed recently in a new study, Zacks [15]. The problem can be described in the following terms.

A number of clusters, k, containing $N_1,\ldots,N_k$ mines, are distributed randomly over a (rectangular) field of specified dimensions. The centers of the clusters $(\xi_1,\zeta_1),\ldots,(\xi_k,\zeta_k)$ are given and the specific bivariate distribution functions, according to which the mines in each cluster are distributed, are given too. The problem is to determine, for any specific breaching path, the survival probabilities of each one of n targets (personnel, vehicles or tanks) crossing in a column at the same path; under the following assumptions:

(i) the encounters of targets and mines are conditionally independent of the prior events;

(ii) with probability p_{det} a mine is detected and destroyed by the target;

(iii) an activated mine destroys the target only with probability p_k;

(iv) a target passing the neighborhood of a mine activates it with probability p_{act}.

The parameters p_{det}, p_k and p_{act} are specific to the type of target crossing the field and the type of mine used.

The survival probabilities of the targets crossing in a column depend in addition on the number of mines in the path. This is an unknown variable, whose distribution can be often approximated by a Poisson distribution, with parameter, λ, which depends on the location of the path relative to the centers of the k clusters; on the number of mines $N_1,\ldots,N_k$; and on the particular distributions of the clusters. In a recent paper Zacks [15] provided formulae for the determination of the parameter

λ when the cluster distributions are bivariate normal, and an algorithm for the recursive (exact) determination of the survival probabilities. In the previous papers of Zacks and Goldfarb [11] and of Parsons [7] closed form formulae were provided for the survival probabilities in the speical case of no possible detection ($p_{det} = 0$) and every activation destroys the target ($p_k = 1$). Closed analytic formulae can be derived also in the present general model. They are however, of no speical interest, because the computation time required is trivial. The procedure developed by Zacks in [15] has been already appied by TRASANA at the White Sands Missile Base for the solution of various problems in the evaluation of new weapon systems.

5.0 Example. Consider a square mine field of dimensions 200m x 200m. Nine clusters of $N = 50$ mines are distributed over the field around the center points with coordinates $\xi_i = 50, 100, 150$ m and $\zeta_i = 50, 100, 150$ m $(i = 1,2,3)$. Each cluster is distributed according to a bivariate normal distribution around its center point with variances $\sigma_x^2 = 81.25\ m^2$, $\sigma_y^2 = 43.75\ m^2$ and correlation $\rho = .5447$. Such a distribution is obtained by a $\theta = 30^\circ$ rotation of a bivariate normal distribution with $\sigma_y = 10m$, $\sigma_y = 5m$ and $\rho = 0$.

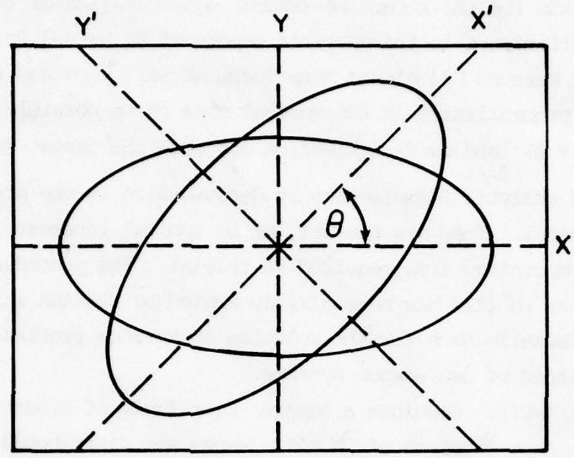

Figure 2. Ellipsoids of concentration of scatter distributions.

We consider straight breaching paths of width lm. We compute first the probability ψ_{ij}, that a mine belonging to cluster (i,j) will fall in the breaching path. The distribution of the number of mines in the path is approximated by a Poisson distribution with mean $\lambda^* = 50 \sum_{i=1}^{3} \sum_{j=1}^{3} \psi_{ij}$. Following the algorithm developed in [15] we can determine the expected number of survivors in a column of n. In the following table we provide the values of λ^* and expected survivors in 20 paths located B m from the center of the field.

Table 4. Expected number of survivors in columns of $n=10$, $p_{det}=.4$, $p_{act}=.95$, $p_k=.7$, $p_{dud}=.2$, $n=50$.

B	λ^*	$E\{X_n\}$
-95.	0.000	10.000
-85.	0.003	9.999
-75.	0.114	9.953
-65.	1.331	9.452
-55.	4.552	8.127
-45.	4.552	8.127
-35.	1.334	9.451
-25.	0.228	9.906
-15.	1.334	9.451
- 5.	4.552	8.127
5.	4.552	8.127
15.	1.334	9.451
25.	0.228	9.906
35.	1.334	9.451
45.	4.552	8.127
55.	4.552	8.127
65.	1.331	9.452
75.	0.114	9.953
85.	0.003	9.999
95.	0.000	10.000
Average		9.259

There are several interesting statistical problems that can be tackled now. One is the problem of optimal strategies of crossing a field when there is no complete information on the scatter distributions of the mines in each cluster and on the number of mines in each cluster. If this information is available we can easily find the path for which the expected number of surviving targets, out of n crossing in a column, is maximal. One can impose on this maximization problem also additional constraints of the battlefield. On the other hand, when the information needed to compute the distribution of the number of mines in each path is incomplete the decision problem becomes that of choosing from m alternative paths one having the most favorable distribution of the number of mines in the path. The decision of

how to cross the n targets is performed in a sequential manner. According to some prior consideration a crossing path is chosen for the first target. The result of the first crossing attempt (success or failure and the points along the path at which mines were destroyed) leads to a reevaluation of the strategy and a crossing path for the second target is then chosen, and so on. The objective is to find a decision rule for maximizing the expected number of survivors. Zacks [8] studied the problem previously for the case of two crossing paths, in terms of the famous TWO ARMED BANDIT PROBLEM. It is an interesting and quite difficult problem that should be studied. Algorithms of the Dynamic Programming type for the optimal determination of the corssing strategy can be developed.

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REMARKS ON THE PRESENTATIONS OF
S. ZACKS AND LT. GENL. W. L. CREECH

by J. R. THOMPSON
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I should first like to thank Professor Zacks for his explication of three very interesting stochastic problems. I will comment briefly about each.

In the inventory problem, it would be interesting to carry out robustness studies to determine the sensitivity of the criterion function of the proposed strategy if one has picked an incorrect distribution for the demand variables.

In the manpower forecasting model, I did not fully understand the prediction lead time being used. The Box-Jenkins ARIMA models do very well if the prediction time is short but frequently deteriorate if the lead time is long enough to be useful. Does the alternative procedure proposed by Professor Zacks overcome this difficulty? A number of seemingly important variables are left out of the model--e.g., the unemployment rate in the civilian sector.

The mine field crossing problem has, I believe, more application for nonwestern armies than for our own. During the Second World War, the Red Army, with the assistance of thousands of Political Commissars, was able to use tactics which were virtually unchanged by the detection of minefields. From a coldblooded standpoint of efficiency, such a policy is fine. However, I do not believe even Waffen SS commanders tried very often to push their men through minefields. And if an American platoon commander called to a private indicating his cannonical path through a minefield, I should have thought it very unlikely the private would cheerily respond, "Airborne, Sir!" and plunge right in. Of course I may be underestimating the motivation and overestimating the

intelligence of the American fighting man.

Finally, I should like to make a comment about a point raised by General Creech yesterday afternoon. The General was concerned about the attempt of some to replace the decision making function of experienced field commanders by the use of cleaver decision theoretic models. In my view, this concern is well placed.

Twenty years ago, before the advent of Secretary McNamara, most military decisions were made by seasoned heuresticians who were blissfully ignorant of systems analysis but who knew military history very well and had natural and developed human abilities to synthesize reliable and fuzzy data streams to formulate policy in the absence of any exhibitable objective function. The main purpose of supporting applied mathematicians was to render as reliable as possible the data streams--not to build decision theoretic models.

With McNamara, this policy changed. His civilian experts busily built decision theoretic models which were supposed to majorize the frankly heuristic approaches of the generals. In point of fact, history has shown that McNamara's models could have been majorized by the most ordinary of company commanders. Our Vietnam debacle and defeat was the first instance in history where a war was lost by the incorrect use of applied mathematics. The generals who protested McNamara's policies early on (and quickly became silent) have been vindicated. McNamara has departed from the DOD to the World Bank where his personal expertise can cost only money. All that is lacking is the endowment of 20 chairs of systems analysis in assorted American universities by the Democratic Republic of Vietnam in gratitude for inadvertent services rendered.

And yet in a very real sense, the policies of McNamara--perhaps useful for business but catastrophic for military purposes--linger on, in fact are well entrenched in the DOD. In 1971, one DOD official told me that he looked forward to the day when every platoon commander in Vietnam would have a portable time

sharing terminal into which data and feelings could be punched and out of which would come action decisions down to the level of the individual rifleman.

Such attitudes are not surprising considering that anyone tends to believe what he hears over and over again. "What's that, Colonel, you're missing a data stream? Not to worry, we'll just Delphi it in for you." "What, General, you don't have an objective function? Our Apples and Oranges Utility Package will create one for you." "What, Admiral, the problem as we have now formulated it defies your intuitions? Of course it does. But just give us a few hundred CPU hours on our 6600 and we'll come up with the answer."

Perhaps some day computer software will surpass the ability of a trained human intellect to combine hard and fuzzy data, hard and fuzzy desiderata into a military decision. That day is not yet come. As yet there exists no viable alternative to the traditional pre-McNamarian forms of military decision making. To paraphrase Clemenceau, war is too important to be left to the systems analysts.

SOME RESULTS ON SUBSET SELECTION PROCEDURES FOR DOUBLE EXPONENTIAL POPULATIONS

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Abstract. A subset selection procedure based on the sample medians for selecting the largest of the location parameters of k double exponential (Laplace) distributions is studied. These unknown location parameters also represent the medians or means of the double exponential populations. An indifference zone approach to the problem of selecting the populations with the t-largest unknown location parameters is discussed. For this distribution the problem of selection for the largest scale parameter is also investigated. A test of homogeneity is proposed which is based on the range of sample medians. Closed forms of the distribution of the statistic associated with the subset selection procedure for location parameters are obtained for some speical cases. Tables of the upper percentage points of this statistic are computed. An example is given to illustrate the use of the selection procedure and the test of homogeneity for the location parameters.

1.0 Introduction. In this paper we study the selection problems and some other related statistical inference problems for k double exponential (Laplace) populations. Before we do this, we give some discussion of the Laplace distribution, its characteristics (vs. normal, logistic and Cauchy) and its use as a model in statistics and probability.

The double exponential distribution arises as a model in some statistical problems as explained later. This distribution is also considered in robustness studies, which suggests that it provides a model with different characteristics than some of the other commonly used models such as the normal distribution. In particular, the tails of the double exponential distribution are

thicker than the tails of the normal or logistic, but not as thick as the Cauchy (see p. 43, Hajek [14]). Yet the double exponential has not been used very extensively as a model. This could be due in part to the lack of available statistical techniques for this distribution, although it is likely that the experimenter has shied away from using the double exponential because it has a sharp peak in the center. However, many applications would be primarily concerned with tail probabilities, and it would seem that the double exponential would be a useful model if exponential tails are required.

The double exponential has some application as a model in the area of Actuarial Science, and it has been suggested as a model for the distribution of the strength of flaws in materials by Epstein [8]. Using the weakest link principle, the strength of the material should decrease as the number of flaws or volume increases. In particular, from extreme-value theory the double exponential assumption leads to the result that the mode or most probable strength decreases in proportion to log n, where n represents the size or number of flaws of the material. In comparison, the assumption of a normal model leads to a decrease in proportion to $(\log n)^{1/2}$. For most applications to material strength, only the minimum flaw strength would ordinarily be observable; however, Epstein [8] suggests that there may be many other types of problems, such as a system of components in series, which might be similar from a statistical point of view. Other possible applications of the double exponential are suggested by the fact that the difference of two independent (not necessary identical) two parameter exponential variables follows the double exponential distribution, and that the logarithm of the ratios of uniform or Pareto variables follows the double exponential distribution.

In classical theory, once having assumed the form of the parent distribution, we can derive a criterion which is appropriate to this assumption. For example, under the assumption of normality, for the comparison of two means we would derive the

t-statistic. It is then customary to justify the use of such a normal theory criterion in the practical circumstance in which normality cannot be guaranteed by arguing that the distribution of the characteristic is but little affected by non-normality of the parent distribution - that is, it is robust under non-normality. However, this argument ignores the fact that if the parent distribution really differed from the normal, the appropriate criterion would no longer be the normal-theory statistic. Box and Tiao [4] reconsidered the analysis of Darwin's paired data on the heights of self and cross-fertilized plants quoted by Fisher in "The Design of Experiments (1935)". In this development the parent distribution is not assumed to be normal, but only a member of the following class of symmetric distributions

$$p(y|\theta,\sigma,\beta) = \frac{1}{\Gamma[1+\frac{1}{2}(1+\beta)]2^{1+\frac{1}{2}(1+\beta)}\sigma} \exp\{-\frac{1}{2}|\frac{y-\theta}{\sigma}|^{2/(1+\beta)}\} \tag{1.1}$$

where $-\infty < y < \infty$, $0 < \sigma < \infty$, $-\infty < \theta < \infty$, $-1 < \beta \leq 1$. This class of distributions includes the normal $(\beta=0)$ and the double exponential $(\beta=1)$, and its kurtosis parameter is β.

If the probability density function of the double exponential is given by

$$f(x,\theta,\sigma) = \frac{1}{2\sigma} e^{-|\frac{x-\theta}{\sigma}|}, \; -\infty < x < \infty, \; -\infty < \theta < \infty, \; \sigma > 0 \tag{1.2}$$

then the mode of the distribution is $x = \theta$ where it has a sharp peak. The expected value and standard deviation of (1.2) are θ and $\sqrt{2}\,\sigma$ respectively. Moments of the standardized double exponential order statistics can be obtained by using the closed-form expressions for the moments of the standardized negative exponential order statistics derived by Epstein and Sobel [9]. Govindarajulu [10] has given the expressions for these moments.

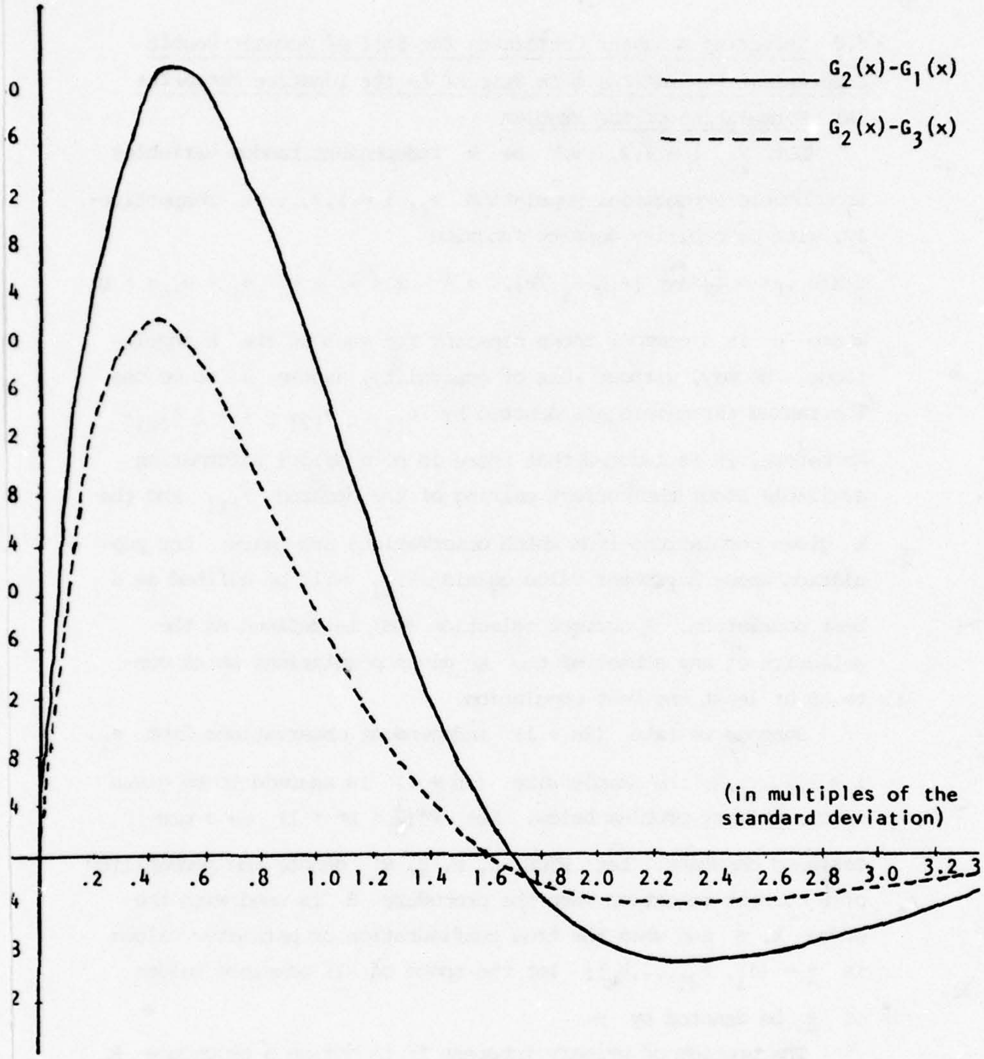
Chew [6] gives the graphs of the standardized density functions of normal, logistic and double exponential distributions,

from which it is clear that the tails of the double exponential distribution are thicker than that of the normal or logistic, in the sense that the curve of double exponential is above that of the others to the left and right of some points. In the case of the normal distribution this point is 2.64.

If the cumulative distribution functions $G_1(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x} e^{-\frac{1}{2}u^2} du$ and $G_2(x) = \begin{cases} \frac{1}{2} e^{\sqrt{2}x}, & x < 0 \\ 1 - \frac{1}{2} e^{-\sqrt{2}x}, & x \geq 0 \end{cases}$ of the standardized normal and double exponential distributions are compared, (also similar comparison between standardized logistic $G_3(x) = 1/(1 + e^{-\frac{\pi}{\sqrt{3}}x})$ and the double exponential distribution) the differences $G_2(x) - G_1(x)$ (as well as $G_2(x) - G_3(x)$) vary in the way shown in the graph below. Since $G_1(x)$, $G_2(x)$ and $G_3(x)$ are symmetric about $x = 0$ only the values for $x \geq 0$ are shown.

With regard to point estimation, it is well known that the maximum likelihood estimates based on the complete sample of size n are given by $\hat{\theta} = \tilde{X}$ and $\hat{\sigma} = \frac{1}{n} \sum_{i=1}^{n} |X_i - \tilde{X}|$, where $\tilde{X}$ denotes the sample median. Also best linear estimators (based on order statistics) under symmetric censoring are given by Govindarajulu [11] for sample sizes up to 20, and some alternate estimates are suggested by Raghunandanan and Srinivasan [16]. Interval estimation for the parameters of the two-parameter double exponential distribution is considered by Bain and Engelhardt [1].

Now we discuss the problem of comparison of $k(\geq 2)$ double exponential distributions. First we study the selection problem for the largest mean (location).



G2(x)-G1(x)
G2(x)-G3(x)
(in multiples of the standard deviation)
.2 .4 .6 .8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4 2.6 2.8 3.0 3.2 3

2.0 *Selecting A Subset Containing the Best of Several Double Exponential Populations With Respect to the Location Parameter*

(A) Formulation of the Problem

Let X_i, $i = 1,2,\ldots,k$ be k independent random variables from double exponential population π_i, $i = 1,2,\ldots,k$ respectively, with probability density function

$$f(X;\theta_i,\sigma) = \frac{1}{2\sigma} \exp\,[-|X-\theta_i|/\sigma], \quad -\infty < x < \infty,\ -\infty < \theta_i < \infty,\ \sigma > 0$$

where σ is a common, known constant for each of the k populations. We may, without loss of generality, assume σ to be one. The ranked parameters are denoted by $\theta_{[1]} \leq \theta_{[2]} \leq \cdots \leq \theta_{[k]}$. As before, it is assumed that there is no a priori information available about the correct pairing of the ordered $\theta_{[i]}$ and the k given populations from which observations are taken. Any population whose parameter value equals $\theta_{[k]}$ will be defined as a best population. A correct selection (CS) is defined as the selection of any subset of the k given populations which contains at least one best population.

Suppose we take $(2n + 1)$ independent observations from π_i, $i = 1,2,\ldots,k$; the sample size $(2n + 1)$ is assumed to be given in the primary problem below. Let $P^*(\frac{1}{k} < P^* < 1)$ be a preassigned constant. Let $P(CS;\, k,\, n,\, \underline{\theta},\, R)$ denote the probability of a correct selection when the procedure R is used with the given k, n and when the true configuration of parameter values is $\underline{\theta} = (\theta_1, \theta_2,\ldots,\theta_k)$; let the space of all possible values of $\underline{\theta}$ be denoted by Ω.

The problem of primary interest is to define a procedure R which selects a subset of the k given populations that is small, never empty, and large enough so that it contains the best population with probability at least P^*, regardless of the true configurations $\underline{\theta}$ in Ω, i.e., so that

$$\inf_{\Omega} P(CS;\ k,\ n,\ \underline{\theta},\ R) \geq P^* . \qquad (2.1)$$

After having defined a particular procedure $R = R(k, n, P^*)$ for each possible set of values of k, n and P^*, we discuss the expected size $E\{S;\ k,\ n,\ \underline{\theta},\ P^*,\ R\}$ of the selected subset when the procedure R is used with the given k, n, P^* and where $\underline{\theta}$ is the true parameter configuration in Ω.

Let Y_i denote the sample median of the $(2n+1)$ observations $X_{i1},\ldots,X_{i,2n+1}$, from the ith population, and let $Y_{(i)}$ denote that unknown variable which is associated with $\theta_{[i]}$. The probability density $g_n(\cdot)$ and the cumulative distribution $G_n(\cdot)$ of Y_i are given by

$$g_n(y;\ \theta_i) = \frac{(2n+1)!}{n!n!}\left(\frac{1}{2}e^{-|y-\theta_i|}\right)^{n+1}\left(1 - \frac{1}{2}e^{-|y-\theta_i|}\right)^{n} \qquad (2.2)$$

$$G_n(y;\theta_i) = \begin{cases} 1 - \sum\limits_{j=0}^{n} \binom{2n+1}{j}\left(\frac{1}{2}e^{y-\theta_i}\right)^{j}\left(1 - \frac{1}{2}e^{y-\theta_i}\right)^{2n+1-j}, & y<\theta_i \\[2ex] \sum\limits_{j=0}^{n} \binom{2n+1}{j}\left(\frac{1}{2}e^{-(y-\theta_i)}\right)^{j}\left(1 - \frac{1}{2}e^{-(y-\theta_i)}\right)^{2n+1-j}, & y\geq\theta_i \end{cases} \qquad (2.3)$$

Now, we propose the selection procedure R_1 as follows:

R_1: Retain in the selected subset only those populations π_i for which

$$Y_i \geq \max_{1\leq j\leq k} Y_j - d \qquad (2.4)$$

where $d = d(k, n, P^*)$ is the smallest non-negative constant to be determined that will satisfy the basic probability requirement (2.1) for all configurations $\underline{\theta} = (\theta_1, \theta_2, \ldots, \theta_k)$.

(B) Probability of a Correct Selection and Its Infimum

The following result concerning the rule R_1 can be proved.

Theorem 2.1. $\inf_{\underline{\theta}\in\Omega} P_{\underline{\theta}}(CS|R_1) = \inf_{\underline{\theta}\in\Omega_0} P_{\underline{\theta}}(CS|R_1) = \int_{-\infty}^{\infty} G_n^{k-1}(y+d)g_n(y)dy$

where $\Omega_0 = \{\underline{\theta} = (\theta_1, \ldots, \theta_k): \theta_1 = \theta_2 = \ldots = \theta_k = \theta\}$, $G_n(y)$, $g_n(y)$ are the cdf and pdf of the sample median of $(2n+1)$ observations from the standard double exponential distribution.

Proof. For $\underline{\theta} \in \Omega$,

$$P_{\underline{\theta}}(CS|R_1) = P_{\underline{\theta}}\{Y_{(k)} \geq \max_{1\leq j\leq k} Y_{(j)} - d\}$$

$$= P_{\underline{\theta}}\{Y_{(k)}-\theta_{[k]}\geq Y_{(j)}-\theta_{[j]}+\theta_{[j]}-\theta_{[k]}-d,\ j=1,2,\ldots,k-1\}$$

$$= \int_{-\infty}^{\infty}\left[\prod_{j=1}^{k-1}\int_{-\infty}^{y+\theta_{[k]}-\theta_{[j]}+d} g_n(z)\,dz\right] g_n(y)\,dy. \tag{2.5}$$

Note that $\theta_{[k]} - \theta_{[j]} \geq 0$ for $j = 1, \ldots, k-1$; thus the result follows. Hence, if we choose d to be the smallest constant to satisfy

$$\int_{-\infty}^{\infty} G_n^{k-1}(y+d)\, g_n(y)\, dy = P^*, \tag{2.6}$$

then we have determined the constant d for which

$$\inf_{\underline{\theta}\in\Omega} P_{\underline{\theta}}(CS|R_1) = P^*. \tag{2.7}$$

(C) Some properties of R_1

For $\underline{\theta} \in \Omega$ and $\underline{\theta} = (\theta_{[1]},\ldots,\theta_{[k]})$ define $P_{\underline{\theta}}(i) = P_{\underline{\theta}}$ {R select population $\pi_{(i)}$}, and recall the following definitions (see Santner [17]).

Definition 2.1. The rule R is strongly monotone in $\pi_{(i)}$ means

$$P_{\underline{\theta}}(i) \text{ is } \begin{cases} \uparrow \text{ in } \theta_{[i]} \text{ when all other components of } \underline{\theta} \text{ are fixed} \\ \\ \downarrow \text{ in } \theta_{[j]} \ (j \neq i) \text{ when all other components of } \underline{\theta} \text{ are fixed} \end{cases}$$

Definition 2.2. R is a monotone procedure means for every $\underline{\theta} \varepsilon \Omega$ and $1 \leq i < j \leq k$, $P_{\underline{\theta}}(i) \leq P_{\underline{\theta}}(j)$.

Definition 2.3. R is an unbiased procedure means for every $\underline{\theta} \varepsilon \Omega$ and $1 \leq j < k$,

$$P_{\underline{\theta}}\{R \text{ does not select } \pi_{(i)}\} \geq P_{\underline{\theta}}\{R \text{ does not select } \pi_{(k)}\}$$

of course, if R is monotone it is also unbiased.

Theorem 2.2. For any $i = 1,2,\ldots,k$, the procedure R_1 is strongly monotone in $\pi_{(i)}$.

Proof. The proof follows easily from the expression

$$P_{\underline{\theta}}(i) = \int_{-\infty}^{\infty} \{ \prod_{\substack{j=1 \\ j \neq i}}^{k} G_n(y + \theta_{[i]} - \theta_{[j]} + d)\} g_n(y)\, dy \, .$$

Corollary 2.1. The rule R_1 is monotone and unbiased.

Proof. It is known and easy to see that if R is strongly monotone in $\pi_{(i)}$, for all $i = 1,2,\ldots,k$, then it is monotone.

Now we consider some special configurations of $\underline{\theta} \varepsilon \Omega$.

$$\begin{cases} \theta_{[i]} = \theta \quad , \quad i = 1,2,\ldots,k-1 \\ \theta_{[k]} = \theta + \Delta, \quad \Delta > 0 \end{cases} \tag{2.8}$$

$$\theta_{[i]} = \theta + (i-1)\Delta, \ \Delta > 0, \ i = 1,2,\ldots,k. \tag{2.9}$$

Under (2.8),

$$P_{\underline{\theta}}(i) = \int_{-\infty}^{\infty} [G_n(y+d)]^{k-2} G_n(y+d-\Delta)\, g_n(y)\, dy \text{ for } i=1,2,\ldots,k-1 \tag{2.10}$$

$$P_{\underline{\theta}}(k) = \int_{-\infty}^{\infty} [G_n(y+d+\Delta)]^{k-1}\, g_n(y)\, dy \, . \tag{2.11}$$

While under (2.9),

$$p_{\underline{\theta}}(i) = \int_{-\infty}^{\infty} \{ \prod_{\substack{j=1\\ j\neq i}}^{k} G_n(y+d+(i-j)\Delta)\} g_n(y)\, dy, \; i=1,2,\ldots,k.$$

From the above equations we can make the following remarks:

Remark 2.1. For fixed P^*, k, n, i ($i = 1, 2, \ldots, k-1$), the probability of selecting population $\pi_{(i)}$ decreases from P^* to zero as Δ increases from zero to infinity.

Remark 2.2. For fixed P^*, k and n, the probability of selecting $\pi_{(k)}$ increases from P^* to one as Δ increases from zero to infinity.

Remark 2.3. For fixed P^*, k, $i(i = 1,\ldots,k-1)$ and Δ, the probability of selecting population $\pi_{(i)}$ tends to zero as $n \to \infty$. While the probability of selecting $\pi_{(k)}$ tends to one as $n \to \infty$.

Conclusion: Under either configuration (2.8), (2.9),

$E_{\underline{\theta}}(S|R_1) = \sum_{i=1}^{k} p_{\underline{\theta}}(i) \to 1$ as $\Delta \to \infty$ for fixed n and $E_{\underline{\theta}}(S|R_1) \to 1$ as $n \to \infty$ for fixed Δ.

(D) Asymptotic Results for the Procedure R_1

It suffices to consider the parameter space Ω_o. For n large, we discuss an asymptotic property of the procedure as follows. Let Y be the sample median from a sample of size $(2n+1)$ with pdf $f(x;\theta) = \frac{1}{2} e^{-|x-\theta|}$, $-\infty < x < \infty$. Then it is known (see Chu [7]) that under Ω_o, $\frac{Y-\theta}{\sigma_n}$ is asymptotically normally distributed (here $\sigma_n^2 = \frac{1}{2n+1}$). Let Z denote a random variable which has a standard normal distribution then $\frac{Y-\theta}{\sigma_n}$ is asymptotically distributed as Z. Hence, under Ω_o, the probability of

$$Y_k \geq \max_{1\leq j\leq k} Y_j - d$$

is asymptotically, the same as the probability of

$$Z_k \geq \max_{1 \geq j \geq k} Z_j - \sqrt{2n+1}\, d \qquad (2.13)$$

where Z_i, $i = 1,2,\ldots,k$, are iid standard normal variables.

Hence,

$$\inf_{\underline{\theta} \varepsilon \Omega_o} P_{\underline{\theta}}(CS|R_1) \approx P\{Z_k \geq \max_{1 \leq j \leq k} Z_j - \sqrt{2n+1}\, d\}$$

$$= \int_{-\infty}^{\infty} \Phi(z + \sqrt{2n+1}\, d)^{k-1} \, d\Phi(z)$$

where $\Phi(\cdot)$ is the cdf of the standard normal distribution.

(E) The Monotone Likelihood Ratio Property of the Sample Median

Suppose Y is the sample median of $(2n+1)$ observations from the population with double exponential density function $f(x;\theta) = \frac{1}{2} e^{-|x-\theta|}$. The pdf $g_n(y;\theta)$ and cdf $G_n(y;\theta)$ of Y are given by equations (2.2) and (2.3).

After some algebraic computations, we see that $G_n(\theta;\theta) = \frac{1}{2}$; also it is easy to show that $g_n(y;\theta)$ is continuous at $y = \theta$.

Let $g_n(y;\theta) = \bar{g}_n(y-\theta)$. It is shown in Lehmann [15, p. 330] that a necessary and sufficient condition for $\bar{g}_n(y-\theta)$ to have monotone likelihood ratio in y is that $-\log \bar{g}_n$ is convex. Our main goal in this section is to prove this assertion. Now

$$\bar{g}_n(y) = c_n\left(\frac{1}{2} e^{-|y|}\right)^{n+1}\left(1 - \frac{1}{2} e^{-|y|}\right)^n \text{ where } c_n = \frac{(2n+1)!}{n!n!}, \text{ so,}$$

$$-\log \bar{g}_n(y) = -\log c_n + (n+1)\log 2 + (n+1)|y| - n\log\left(1 - \frac{1}{2} e^{-|y|}\right).$$

Let $h(y) = (n+1)|y| - n\log\left(1 - \frac{1}{2} e^{-|y|}\right) = \begin{cases} h_1(y), & y < 0 \\ h_2(y), & y \geq 0 \end{cases}$ which is

a continuous function. For $y < 0$,

$$h(y) = h_1(y) = -(n+1)y - n \log (1 - \frac{1}{2} e^y), \text{ we have}$$

$$h_1'(y) = -(n+1) + \frac{\frac{n}{2} e^y}{1 - \frac{1}{2} e^y} < 0 \text{ since for } y < 0, \frac{\frac{1}{2} e^y}{1 - \frac{1}{2} e^y} < 1$$

$$\text{and} \quad h_1''(y) = \frac{\frac{n}{2} e^y}{(1 - \frac{1}{2} e^y)^2} > 0.$$

Hence, for $y < 0$, $h_1(y)$ is a decreasing, convex function. Similarly, for $y \geq 0$,

$$h(y) = h_2(y) = (n+1)\, y - n \log (1 - \frac{1}{2} e^{-y})$$

$$h_2'(y) = n+1 - \frac{\frac{n}{2} e^{-y}}{1 - \frac{1}{2} e^{-y}} > 0 \text{ since for } y \geq 0, \frac{\frac{1}{2} e^{-y}}{1 - \frac{1}{2} e^{-y}} < 1$$

$$h_2''(y) = \frac{\frac{n}{2} e^{-y}}{(1 - \frac{1}{2} e^{-y})^2} > 0.$$

Hence, for $y \geq 0$, $h_2(y)$ is an increasing, convex function. Note that $h(y)$ is continuous at $y = 0$, decreasing, convex for $y < 0$ and increasing, convex for $y \geq 0$. Hence, this concludes that $h(y)$ is a convex function, which implies $- \log \bar{g}_n(y)$ is also a convex function.

Theorem 2.3. $g_n(y;\theta)$ has monotone likelihood ratio in y.

(F) Expected Size of the Selected Subset

The procedure R_1 satisfies the basic probability requirement (2.1) and is defined by (2.4). Consistent with the basic probability requirement, we would like the size of the selected subset to be small. Now S, the size of the selected subset is a random variable which takes integer values 1,2,...,k. Hence, one criterion of the efficiency of the procedure R_1 is the expected

value of the size of the subset. Now we derive an expression for $E(S|R_1)$, the expected size of the selected subset using procedure R_1.

$$E(S|R_1) = \sum_{i=1}^{k} P\{\text{Selecting the population with parameter } \theta_{[i]}\}$$

$$= \sum_{i=1}^{k} P\{Y_{(i)} \geq \max_{1 \leq j \leq k} Y_{(j)} - d\}$$

$$= \sum_{i=1}^{k} \int_{-\infty}^{\infty} \left[\prod_{\substack{j=1 \\ j \neq i}}^{k} G_n(y + d + \theta_{[i]} - \theta_{[j]})\right] g_n(y)\, dy. \quad (2.16)$$

If we set the m smallest parameters θ_i $(1 \leq m < k)$ equal to a common value θ (say) and define

$$Q = E(S \mid \theta_{[1]} = \ldots = \theta_{[m]} = \theta) \quad (2.17)$$

then by an analogous argument as in Gupta [13] one can prove the following theorem.

Theorem 2.4. For given k, $P^*(\frac{1}{k} < P^* < 1)$, the expected size of the selected subset $E(S \mid \theta_{[1]} = \theta_{[2]} = \ldots = \theta_{[m]} = \theta,\ m < k)$ in using the procedure R_1 is strictly increasing in θ.

Corollary 2.2. $\sup_{\underline{\theta} \in \Omega} E_{\underline{\theta}}(S|R_1) = k \int_{\infty}^{\infty} G_n^{k-1}(y+d) g_n(y)\, dy = k P^*$.

Corollary 2.3. In the subset $\Omega(\delta) = \{\underline{\theta}: \theta_{[i]} \leq \theta_{[k]} - \delta,$ $i = 1,2,\ldots,k-1\}$, the function $E_{\underline{\theta}}(S|R_1)$ takes on its maximum value when $\theta_{[i]} = \theta_{[k]} - \delta$, $i = 1,2,\ldots,k-1$, and so

$$\sup_{\underline{\theta} \in \Omega(\delta)} E_{\underline{\theta}}(S|R_1) = \int_{-\infty}^{\infty} G_n^{k-1}(y+d+\delta)\, g_n(y)\, dy$$

$$+ (k-1) \int_{-\infty}^{\infty} G_n^{k-2}(y+d)\, G_n(y+d-\delta)\, g_n(y)\, dy .$$

(G) Minimax Property of the Rule R_1

Suppose that $y_1,\ldots,y_k$ are the sample medians from the k populations $\pi_1,\ldots,\pi_k$, respectively, and with this set of observations, we select the ith population with probability $\phi_i(y_1,\ldots,y_k)$. Then the selection rule R is said to be invariant or symmetric if

$$\phi_i(y_1,\ldots,y_i,\ldots,y_j,\ldots,y_k) = \phi_j(y_1,\ldots,y_j,\ldots,y_i,\ldots,y_k)$$

for all i and j, i.e. if y_j is observed from π_i and y_i from π_j, then we select the jth population with the same probability $\phi_i(y_1,\ldots,y_k)$.

Notice that the rule R_1: $Y_i \geq \max_{1\leq j\leq k} Y_j - d$ satisfies the equations

$$\inf_{\underline{\theta}\varepsilon\Omega} P_{\underline{\theta}}(CS|R_1) = \inf_{\underline{\theta}\varepsilon\Omega_o} P_{\underline{\theta}}(CS|R_1) = P_{\underline{\theta}_o}(CS|R_1) = P^* \qquad (2.20)$$

and
$$\sup_{\underline{\theta}\varepsilon\Omega} E_{\underline{\theta}}(S|R_1) = \sup_{\underline{\theta}\varepsilon\Omega_o} E_{\underline{\theta}}(S|R_1) = E_{\underline{\theta}_o}(S|R_1) = k\,P^* \qquad (2.21)$$

where $\underline{\theta}_o = (\theta_o,\ldots,\theta_o)$.

For any invariant rule R', $\underline{\theta}_o \varepsilon \Omega$,

$$E_{\underline{\theta}_o}(S|R') = \sum_{i=1}^{k} P_{\underline{\theta}_o}\{\text{select population } \pi_i|R'\}$$

$$= \sum_{i=1}^{k} \int \phi_i(y_1,\ldots,y_k) \left[\prod_{j=1}^{k} g_n(y_j)\right] dy_1 \ldots dy_k$$

$$= k\, P_{\underline{\theta}_o}(CS|R').$$

Hence for $\underline{\theta}_o \in \Omega_o$,

$$E_{\underline{\theta}_o}(S|R') - E_{\underline{\theta}_o}(S|R_1) = k\,[P_{\underline{\theta}_o}(CS|R') - P_{\underline{\theta}_o}(CS|R_1)] \qquad (2.22)$$

If the rule R' satisfies the basic P^* condition, it follows from (2.20) that the right hand side of (2.22) is non-negative. Thus

$$E_{\underline{\theta}_o}(S|R') \geq E_{\underline{\theta}_o}(S|R_1) = \sup_{\underline{\theta}\in\Omega} E_{\underline{\theta}}(S|R_1).$$

So that $\sup\limits_{\underline{\theta}\in\Omega} E_\theta(S|R') \geq \sup\limits_{\underline{\theta}\in\Omega} E_\theta(S|R_1)$

i.e the rule R_1 is minimax among all invariant rules satisfying the P^*-condition.

3.0 Selecting the Population with the Largest Location Parameter-Indifference Zone Approach. In this section, we would like to use the indifference zone approach of Bechhofer [3] to select one population which is guaranteed to be associated with the largest location parameter with a fixed probability P^* whenever the unknown parameters lie outside some subset, or zone of indifference, of the entire parameter space. The goal is to define a sequence of rules $\{R_2(n)\}$ each of which selects a single population $\pi_{(k)}$ and find the smallest n so that

$$P_{\underline{\theta}}(CS|R_2(n)) \geq P^*, \quad \underline{\theta}\in\Omega(\delta^*) = \{\underline{\theta}: \theta_{[k]} - \theta_{[k-1]} \geq \delta^*\} \qquad (3.1)$$

where P^* and δ^* are preassigned numbers.

For the sake of clarity, we will use the notation $Y_{[k]n}$ to denote the largest of the sample medians each based on $(2n + 1)$ observations. $R_2(n)$: Select the population corresponding to $Y_{[k]n}$.

Let $\Omega_o(\delta^*) = \{\underline{\theta}:\theta_{[1]} = \dots = \theta_{[k-1]} = \theta_{[k]} - \delta^*\}$. Then we have the following theorem.

Theorem 3.1. $\inf_{\underline{\theta}\varepsilon\Omega(\delta^*)} P_{\underline{\theta}}(CS|R_2(n)) = \inf_{\underline{\theta}\varepsilon\Omega_o(\delta^*)} P_{\underline{\theta}}(CS|R_2(n))$

Proof. For $\underline{\theta} \varepsilon \Omega(\delta^*)$,

$$P_{\underline{\theta}}(CS|R_2(n)) = P_{\underline{\theta}}\{\max_{1\le j\le k-1} Y_{(j)n} < Y_{(k)n}\}$$

$$= P_{\underline{\theta}}\{Y_{(j)n} < Y_{(k)n},\ j = 1,2,\dots,k-1\}$$

$$= P_{\underline{\theta}}\{Y_{(j)n}-\theta_{[j]} < Y_{(k)n}-\theta_{[k]}+\theta_{[k]}-\theta_{[j]},\ j=1,2,\dots,k-1\}$$

$$= \int_{-\infty}^{\infty}\left[\prod_{j=1}^{k-1} G_n(y + \delta_{kj})\right] d\, G_n(y) \tag{3.2}$$

where $G_n(y) = G_n(y;\ 0)$ is the cdf of the sample median of $(2n+1)$ independent observation from the standard double exponential distribution with density function $\frac{1}{2} e^{-|x|}$, $-\infty < x < \infty$, and $\delta_{kj} = \theta_{[k]} - \theta_{[j]} \ge 0$. Hence the infimum of the probability of a correct selection occurs when $\theta_{[1]} = \theta_{[2]} = \dots = \theta_{[k-1]} = \theta_{[k]} - \delta^*$ provided $\theta_{[k]} - \theta_{[k-1]} \ge \delta^*$. This proves the theorem.

The minimum sample size required to achieve the P^* condition (3.1) is the smallest integer n such that

$$\int_{-\infty}^{\infty} [G_n(y + \delta^*)]^{k-1}\, d\, G_n(y) \ge P^*. \tag{3.3}$$

4.0 Selecting the t-Best Populations - Indifference Zone Approach. Now, we consider the problem of selecting the best t populations, i.e., the populations with location parameters $\theta_{[k-t+1]}, \theta_{[k-t+2]}, \dots, \theta_{[k]}$, without regard to order. We are using the indifference zone approach based on the sampe median Y_i of $2n+1$ independent

observations from population π_i, $i = 1,\ldots,k$. Define a sequence of procedures as follows: $R_3(n)$: Select the t populations associated with t largest values of Y_i.

Let $\Omega'(\delta^*) = \{\underline{\theta}: \theta_{[k-t+1]} - \theta_{[k-t]} \geq \delta^*\}$ and let

$$\Omega_o'(\delta^*) = \{\underline{\theta}: \theta_{[1]}=\ldots=\theta_{[k-t]}=\theta,\ \theta_{[k-t+1]}=\ldots=\theta_{[k]} = \theta+\delta^*\}.$$

<u>*Theorem 4.1.*</u> $\inf\limits_{\underline{\theta}\in\Omega'(\delta^*)} P_{\underline{\theta}}\{CS|R_3(n)\} = \inf\limits_{\underline{\theta}\in\Omega_o(\delta^*)} P_{\underline{\theta}}\{CS|R_3(n)\}$

<u>*Proof.*</u> It was shown in Theorem 2.3 that the pdf $g_n(y;\ 0)$ of the sample median has monotone likelihood ration in y, which implies that it is stochastically increasing in θ. Using a theorem of Barr and Rizvi [2], it follows that, for $\underline{\theta} \in \Omega'(\delta^*)$

$$P_{\underline{\theta}}\{CS|R_3(n)\} = P_{\underline{\theta}}\{\max_{1\leq i\leq k-t} Y_{(i)} < \min_{k-t+1\leq j\leq k} Y_{(j)}\}$$

is a non-increasing function of $\theta_1,\ldots,\theta_{k-t}$ and a non-decreasing function of $\theta_{k-t+1},\ldots,\theta_k$. Thus $P_{\underline{\theta}}\{CS|R_3(n)\}$ attains its infimum when $\theta_{[1]},\ldots,\theta_{[k-t]}$ attain their maximum possible values, while $\theta_{[k-t+1]},\ldots,\theta_{[k]}$ attain their minimum possible values subject to $\underline{\theta} \in \Omega'(\delta^*)$. The proof is thus completed.

Using the same notation as in section 2, let $G_n(y;\theta_i)$ denote the cdf of the sample median Y_i with parameter θ_i. Since θ_i is the location parameter, $G_n(y;\ \theta_i) = G_n(y - \theta_i;\ 0)$ and G_n is stochastically increasing, continuous in both y and θ_i. For $\underline{\theta} \in \Omega'(\delta^*)$,

$$P_{\underline{\theta}}\{CS|R_3(n)\} = P_{\underline{\theta}}\{\max_{1\le i\le k-t} Y_{(i)} < \min_{k-t+1\le \ell\le k} Y_{(\ell)}\}$$

$$= P_{\underline{\theta}}\{\bigcup_{j=k-t+1}^{k} \{Y_{(j)} = \min_{k-t+1\le\ell\le k} Y_{(\ell)} \text{ and } \max_{1\le i\le k-t} Y_{(i)} < Y_{(j)}\}\}$$

$$= \sum_{j=k-t+1}^{k} \int_{-\infty}^{\infty} \prod_{\beta=1}^{k-t} G_n(y;\theta_{[\beta]}) \prod_{\substack{\alpha=k-t+1\\ \alpha\neq j}}^{k} \{1 - G_n(y;\theta_{[\alpha]})\}\, d\, G_n(y;\, \theta_{[j]}).$$

In particular, for $\underline{\theta} \in \Omega_0'(\delta^*) \subset \Omega'(\delta^*)$,

$$P_{\underline{\theta}}\{CS|R\ (n)\} = t \int_{-\infty}^{\infty} G_n^{k-t}(y;\theta)\ \{1 - G_n(y;\theta+\delta^*)\}^{t-1}\ dG_n(y,\theta+\delta^*)$$

$$= t \int_{-\infty}^{\infty} G_n^{k-t}(y-\theta;0)\{1-G_n(y-\theta-\delta^*;0)\}^{t-1} dG_n(y-\theta-\delta^*;0)$$

$$= t \int_{-\infty}^{\infty} G_n^{k-t}(y+\delta^*;0)\ \{1 - G_n(y;0)\}^{t-1}\ dG_n(y;0)$$

which is independent of the parameter θ. Hence for specified values of δ^* and P^* $\left(\frac{1}{\binom{k}{t}} < P^* < 1\right)$, we can solve the equation

$$t \int_{-\infty}^{\infty} G_n^{k-t}\ (y + \delta^*;\ 0)\ \{1 - G_n(y;\ 0)\}^{t-1}\ dG_n(y;\ 0) = P^*$$

for n.

5.0 Subset Selection with Respect to the Scale Parameter. Let X_i, $i = 1,2,\ldots,k$ be k independent random variables from double exponential populations π_i, $i = 1,2,\ldots,k$, respectively, with π_i having the probability density function

$$f(x;\theta_i,\sigma_i) = \frac{1}{2\sigma_i} \exp\ [-|x-\theta_i|/\sigma_i],\ -\infty < x < \infty,\ -\infty < \theta_i < \infty,\ \sigma_i > 0.$$

Take n independent observations from π_i, $i = 1,2,\ldots,k$. From these data one wishes to select a subset containing the population with the largest σ_i. Let $\sigma_{[1]} \leq \cdots \leq \sigma_{[k]}$ be the ordered parameters. We consider two different cases.

Case (i): $\theta_1, \theta_2, \ldots, \theta_k$ known.

In this case, the maximum likelihood estimator of σ_i is $Y_i = \frac{1}{n}\sum_{j=1}^{n} |X_{ij} - \theta_i|$ which is distributed as a gamma variable with parameters n and $\frac{\sigma_i}{n}$, i.e. Y_i has density

$$\frac{n}{\sigma_i \Gamma(n)} \left(\frac{ny}{\sigma_i}\right)^{n-1} e^{-\frac{ny}{\sigma_i}}, \; y > 0.$$

Thus the problem reduces to the one considered by Gupta [12]. The selection procedure is

R: Select the population π_i in the subset if and only if

$$Y_i \geq c \max_{1 \leq j \leq k} Y_j.$$

Case (ii): θ_i's are unknown.

When θ_i is unknown, it is well known that the maximum likelihood estimate of σ_i is given by $\hat{\sigma}_i = \frac{1}{n}\sum_{j=1}^{n} |X_{ij} - \tilde{X}_i|$, where $\tilde{X}_i$ denotes the sample median from population π_i. For this problem, we propose the following selection procedure.

R_4: Select the population π_i in the subset if and only if

$$\hat{\sigma}_i \geq c_4 \max_{1 \leq j \leq k} \hat{\sigma}_j$$

where $0 < c_4 < 1$ is so determined as to satisfy the basic probability requirement regardless of what the unknown σ_i's may be.

Let $V_i = \dfrac{n\hat{\sigma}_i}{\sigma_i}$, $i = 1,2,\ldots,k$. Then

$$P(CS|R_4) = P\{\hat{\sigma}_{(k)} \geq c_4 \max_{1\leq j\leq k-1} \hat{\sigma}_{(j)}\}$$

$$= \int_0^\infty \prod_{j=1}^{k-1} F_{V_{(j)}} \left(\frac{1}{c_4} \frac{\sigma_{[k]}}{\sigma_{[j]}} x\right) \, dF_{V_{(k)}}(x).$$

So

$$\inf_{\underline{\sigma}\in\Omega'} P(CS|R_4) = \inf_{\underline{\sigma}\in\Omega'_0} P(CS|R_4) = \int_0^\infty F_V^{k-1} \left(\frac{x}{c_4}\right) dF_V(x),$$

where $\Omega' = \{\underline{\sigma} = (\sigma_1,\ldots,\sigma_k),\ \sigma_i > 0,\ i = 1,\ldots,k\}$,

$\Omega'_0 = \{\underline{\sigma} = (\sigma,\ldots,\sigma),\ \sigma > 0\}$ and $F_V(\cdot)$, $F_{V_{(j)}}(\cdot)$, $j = 1,\ldots,k$ are

the cdf's of $V = \dfrac{n\hat{\sigma}}{\sigma}$, $V_{(j)} = \dfrac{n\hat{\sigma}_{(j)}}{\sigma_{[j]}}$, $j = 1,\ldots,k$, respectively.

Hence if the distribution $F_V(\cdot)$ is known, then the constant c_4 can be determined by the equation

$$\int_0^\infty F_V^{k-1} \left(\frac{x}{c_4}\right) dF_V(x) = P^*.$$

The exact distribution F of V is worked out for $n = 3$ by Bain and Engelhardt [1], and a chi-square approximation is also given by them which is quite good even for small n. However, it follows from Chernoff, Gastwirth and Johns [5], that

$\dfrac{1}{\sqrt{n}}(V-n) = \sqrt{n}\left[\dfrac{\hat{\sigma}}{\sigma} - 1\right]$ is asymptotically a standard normal variable. When all σ_i are identical

$$P(CS|R_4) = P\{\hat{\sigma}_k \geq c_4 \hat{\sigma}_j,\ j = 1,\ldots,k-1\}$$

$$= P\{\sqrt{n}\left(\frac{\hat{\sigma}_k}{\sigma} - 1\right) \geq c_4 \sqrt{n}\left(\frac{\hat{\sigma}_j}{\sigma} - 1\right) + \sqrt{n}(c_4-1),\ j = 1,\ldots,k-1\}$$

$$\stackrel{\sim}{=} \int_{-\infty}^{\infty} \Phi^{k-1}\left(\frac{x-\sqrt{n}(c_4-1)}{c_4}\right) d\Phi(x).$$

6.0 A Test of Homogeneity Based on the Sample Median Range. Let $\pi_1, \pi_2, \ldots, \pi_k$ be k independent double exponential populations such that the observations $X_{i1}, \ldots, X_{i,2n+1}$ from π_i has density $\frac{1}{2} e^{-|X-\theta_i|}$, for $i = 1,2,\ldots,k$. As before, let the sample median of these $(2n+1)$ observations be denoted as Y_i, $i = 1,\ldots,k$. In some practical situations one wishes to know whether θ_i are significantly different or not. This problem is to test the homogeneity of the double exponential populations. We are interested in using a test based on the sample range of Y's and hence we wish to derive the distribution of the sample median range $R = \max_{1\le j\le k} Y_j - \min_{1\le j\le k} Y_j$, considering all θ_i to be equal to a common unknown θ. When the value of R is large, the hypothesis of homogeneity is rejected. We wish to find a constant r, such that $P(R > r) \le \alpha$ under the hypothesis H_0: $\theta_1 = \ldots = \theta_k = \theta$. This will provide an α-level test.

Theorem 6.1. For α, $0 < \alpha < 1$, let r be a constant such that

$$P_{\Omega_0}\{Y_k \ge \max_{1\le j\le k-1} Y_j - r\} \ge 1 - \frac{\alpha}{k}.$$

Then $P_{\Omega_0}(R > r) \le \alpha$.

Proof. When H_0 is true, i.e., under Ω_0,

$$P(R > r) = P(\max_{1\le j\le k} Y_j - \min_{1\le j\le k} Y_j > r\}$$

$$\le k - \sum_{i=1}^{k} P\{Y_i \ge \max_{1\le j\le k} Y_j - r\}$$

$$= k - k\, P\{Y_k \ge \max_{1\le j\le k-1} Y_j - r\}$$

$$\leq k - k\cdot\left(1 - \frac{\alpha}{k}\right)$$

$$= \alpha.$$

The above theorem establishes a connection between the selection rule R_1 and the above test for equality of θ's.

7.0 *On the Distribution of the Statistic Associated with R_1.*

Let $Y_i (i = 0,1,\ldots,p)$ be $(p+1)$ independent and identically distributed random variables each representing the median in a random sample of size $(2n+1)$ from a population with standard double exponential density function $f(x) = \frac{1}{2} e^{-|x|}$. Consider the differences $Z_i = Y_i - Y_0 (i = 1,2,\ldots,p)$. The random variables $Z_i (i = 1,2,\ldots,p)$ are correlated and the distribution of the maximum of Z_i is of interest in problems of selecting and ranking for double exponential distribution as explained earlier when discussing R_1. In this section, we give a closed form of the distribution of $Z = \max_{1 \leq i \leq p} Z_i$ for some special cases. We have also computed tables of the upper percentage points of $Z = \max_{1 \leq i \leq p} Z_i$ corresponding to the probability levels $\alpha = P^* =$ 0.75, 0.90, 0.95, 0.99 for $p = 1(1)\,9$, $n = 1(1)10$.

For the special case $P = 1$ $(k=2)$, $n = 1$ (sample size = 3), straight forward integration gives the cdf of Z (see formulae (2.2), (2.3)) as

$$P(Z \leq z) = \int_{-\infty}^{\infty} G(x + z)\, g(x)\, dx$$

$$= 1 - \frac{9}{8} ze^{-2z} - \frac{3}{16} ze^{-3z} + \frac{9}{40} e^{-2z} - \frac{29}{40} e^{-3z}.$$

Again, for $p = 1$ $(k=2)$, $n = 2$, (sample size = 5),

$$p(z \leq z) = 1 - \frac{75}{16} ze^{-3z} - \frac{225}{64} ze^{-4z} - \frac{45}{256} ze^{-5z} + \frac{10975}{1792} e^{-3z}$$

$$- \frac{[illegible]25}{896} e^{-4z} - \frac{203}{256} e^{-5z} .$$

All computations related to and given at the end of this chapter were made on a CDC 6500 using Gauss Laguerre quadratue based on fifteen nodes to perform the numerical integration. Checks on the accuracy of the program for $p = 1$, $n = 1$ showed that these values seem to be correct to three decimal places.

8.0 An Example and Application of the Selection Rule and the Test of Homogeneity. We would like to illustrate the use of the selection procedure and the test of homogeneity of location parameters for double exponential distributions. It is known that the difference of two independent two-parameter exponential variables with the same scale parameter follows a double exponential distribution. Using a statistical package G6-RVP designed by H. Rubin and C. Hinkle at Purdue University, we generated a set of exponential random numbers, from which we obtained 5 sets of double exponential random numbers with location parameters π_i to be 0, 2.5, 3.4, -2.0, -0.65. Let π_i denote the double exponential population with location parameter θ_i and scale parameter 1. The five pseudo-random samples from π_i, $i = 1,\ldots,5$, are given as follows. In each case 9 observations were taken.

π_1	π_2	π_3	π_4	π_5
-3.4839	- .9839	- .0839	-5.4839	-4.1339
-2.6762	- .1762	.7238	-4.6762	-3.3262
- .3129	2.1871	3.0871	-2.3129	- .9629
- .2264	2.2736	3.1736	-2.2264	- .8764
- .1761	2.3239	3.2239	-2.1761	- .8261
.1461	2.6462	3.5462	-1.8538	- .5038
.3033	2.8033	3.7033	-1.6967	- .3467
1.6160	4.1160	5.0160	- .3840	.9660
5.6924	8.1924	9.0924	3.6924	5.0424

Let Y_i = sample median of samples of size 9. Then $Y_1 = -.1761$, $Y_2 = 2.3239$, $Y_3 = 3.2239$, $Y_4 = -2.1761$, $Y_5 = -.8261$. The procedure proposed for selecting a subset to include the popula-

tion with largest location parameter (or median) θ is

R_1: Select population π_i iff $Y_i \geq \max_{1 \leq j \leq 5} Y_j - d$.

For $P^* = 0.95$, the tabulated value of the selection constant d corresponding to $k = 5$ $(p = 4)$ and $n = 4$ is 1.3210, hence R_1 reduces to

R_1: Select population π_i iff $Y_i \geq 3.2239 - 1.3210 = 1.9029$

which selects populations π_2 and π_3 corresponding to the two largest values of sample medians.

For the problem of testing the hypothesis H: $\theta_1 = \theta_2 = \ldots = \theta_5$, let $\alpha = 0.05$, so that $1 - \frac{\alpha}{k} = 1 - \frac{0.05}{5} = 0.99$; again, we find from the table at the end of the paper that the critical value r is 1.7942. Since the sample median range

$$R = \max_{1 \leq j \leq 5} Y_j - \min_{1 \leq j \leq 5} Y_j = 3.2239 - (-2.1761) = 5.4$$

which is greater than the critical value, the hypothesis H: $\theta_1 = \ldots = \theta_5$ is rejected at 5% level of significance.

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Upper 100(1-P*) percentage points of $Z = \max_{1 \le i \le p} (Y_i - Y_o)$ where $Y_o, Y_1, \ldots, Y_p$ are iid sample median random variables in samples of sizes (2n+1) from the standard double exponential (Laplace) distribution.

p \ n	1	2	3	4	5	6	7	8	9	10
1	.6781	.5145	.4274	.3721	.3334	.3049	.2828	.2651	.2504	.2378
	1.3777	1.0311	.8496	.7357	.6568	.5987	.5541	.5184	.4888	.4634
	1.8508	1.3735	1.1261	.9718	.8658	.7885	.7294	.6825	.6436	.6102
	2.8631	2.0931	1.7002	1.4598	1.2994	1.1876	1.1070	1.0464	.9974	.9533
2	1.0434	.7875	.6522	.5667	.5072	.4631	.4289	.4014	.3786	.3591
	1.7380	1.2948	1.0640	.9195	.8195	.7459	.6892	.6437	.6060	.5738
	2.2092	1.6330	1.3354	1.1503	1.0231	.9302	.8590	.8024	.7555	.7513
	3.2186	2.3459	1.9015	1.6297	1.4479	1.3203	1.2274	1.1569	1.0998	1.0489
3	1.2507	.9401	.7767	.6737	.6021	.5490	.5077	.4746	.4470	.4234
	1.9451	1.4445	1.1847	1.0224	.9102	.8275	.7637	.7126	.6703	.6342
	2.4159	1.7811	1.4540	1.2509	1.1114	1.0094	.9313	.8690	.8176	.7735
	3.4247	2.4913	2.0166	1.7265	1.5322	1.3955	1.2956	1.2194	1.1576	1.1029
4	1.3972	1.0468	.8632	.7476	.6673	.6078	.5616	.5244	.4935	.4672
	2.0917	1.5496	1.2689	1.0938	.9729	.8838	.8151	.7601	.7146	.6758
	2.5624	1.8852	1.5369	1.3210	1.1728	1.0644	.9813	.9151	.7605	.8138
	3.5706	2.5936	2.0974	1.7942	1.5911	1.4479	1.3430	1.2629	1.1979	1.1405
5	1.5109	1.1290	.9294	.8040	.7170	.6525	.6024	.5622	.5288	.5003
	2.2053	1.6306	1.3336	1.1485	1.0208	.9268	.8543	.7962	.7482	.7074
	2.6759	1.9655	1.6007	1.3747	1.2197	1.1064	1.0195	.9503	.8932	.8444
	3.6838	2.6727	2.1596	1.8463	1.6363	1.4881	1.3794	1.2962	1.2287	1.1693

p \ n	1	2	3	4	5	6	7	8	9	10
6	1.6039	1.1958	.9830	.8496	.7570	.6885	.6353	.5925	.5571	.5269
	2.2982	1.6965	1.3860	1.1928	1.0595	.9615	.8859	.8253	.7753	.7328
	2.7686	2.0308	1.6524	1.4183	1.2577	1.1403	1.0503	.9787	.9195	.8691
	3.7762	2.7371	2.2101	1.8855	1.6729	1.5207	1.4088	1.3232	1.2537	1.1925
7	1.6826	1.2521	1.0281	.8878	.7905	.7186	.6628	.6179	.5807	.5491
	2.3767	1.7520	1.4301	1.2299	1.0920	.9905	.9134	.8497	.7979	.7540
	2.8470	2.0859	1.6959	1.4548	1.2895	1.1687	1.0762	1.0024	.9416	.8898
	3.8543	2.7913	2.2526	1.9240	1.7037	1.5480	1.4336	1.3458	1.2745	1.2120
8	1.7507	1.3007	1.0669	.9207	.8193	.7444	.6863	.6396	.6009	.5681
	2.4447	1.7999	1.4681	1.2619	1.1199	1.0155	.9350	.8706	.8174	.7722
	2.9148	2.1334	1.7335	1.4863	1.3169	1.1932	1.0984	1.0228	.9606	.9075
	3.9219	2.8338	2.2894	1.9546	1.7302	1.5716	1.4548	1.3653	1.2925	1.2288
9	1.8109	1.3435	1.1010	.9495	.8446	.7670	.7069	.6586	.6186	.5847
	2.5047	1.8421	1.5014	1.2900	1.1444	1.0373	.9548	.8888	.8344	.7881
	2.9747	2.1753	1.7665	1.5139	1.3410	1.2146	1.1178	1.0407	.9772	.9231
	3.9816	2.8796	2.3217	1.9815	1.7535	1.5922	1.4735	1.3823	1.3083	1.2435

For given p,n and P* = .75 (top), .90 (second, .95 (third), .99 (bottom), the entries in this table are the values of d for which $\int_{-\infty}^{\infty} G_n^P(x+d)\, dG_n(x) = P^*$ where $G_n(\cdot)$ is the cdf of the median in a sample of size (2n_1) from the standard double exponential distribution.

CRITICAL PATH ANALYSIS IN STOCHASTIC NETWORKS: STATISTICAL PERT

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Abstract. This paper describes a comprehensive new procedure for obtaining information about the distribution of a project's completion time when the project is comprised of a large number of activities and the time required to complete an individual activity is a random variable. The project is represented as an acyclic network whose arcs correspond to the project's activities. This network is simplified by replacing various activity configurations (blocks of activities) by single equivalent activities. The network is then decomposed into several sub-networks. The distribution and moments of each sub-networks completion time are bounded and approximated on the basis of two percentiles from each activity's completion time distribution by using a new result in the theory of networks. The project's completion time distribution is then approximated by combining the approximate sub-network distributions.

This paper represents a condensation of the five technical reports (see list of references) prepared under a research contract for the Office of Naval Research and titled "Optimization Research." More specifically it has been necessary to omit from this condensation all aspects concerned with the "optimization" of the PERT Networks: The well-known technique in deterministic PERT known under the name of "compression" postulates convex cost functions for the completion of each individual activity. This procedure has been generalized and combined with statistical PERT and the above named technical reports provide a means of minimizing the cost of the completion of the project subject to a speci-

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*Report based on research sponsored by the Operations Research Division of the Office of Naval Research.

fied schedule for either the expected completion time of the project or an upper percentile for the completion time. Generalizations to monitoring the progress of a project at an intermediate phase are also given which optimize in a similar manner that part of the project not as yet completed at the time of monitoring. For details of these techniques reference is again made to the technical reports.

Finally, computer programs are available by courtesy of the Office of Naval Research from Dr. R. L. Sielken, Jr., Institute of Statistics, Texas A&M University, College Station, Texas 77843.

The well-known Program Evaluation and Review Technique (PERT) is concerned with a 'project' comprised of a large number of 'activities' which are arranged as the arcs in an acyclic network (see e.g. Figure 2). The activities at any network node 'commerce' as soon as all activities 'terminating' at that node are completed. The time required to complete an activity once it can be begun is a random variable, and hence the time needed to complet the entire project is also a random variable. The purpose of this paper is to describe and illustrate some new methods for obtaining information concerning the project completion time and its distribution.

The classical PERT approach is to replace each individual activity's random completion time by its mean, and then use the project completion time for this deterministic network as an approximation to the mean completion time for the entire project. It is well-known that this approximation may seriously underestimate the mean project completion time (see e.g. [1]). Another shortcoming of the classical PERT approach is that it provided no information about the distrubition of the project completion time other than an approxim ation of the mean completion time.

The relationship of the project completion time to critical path methodology of course stems from the fact that, for a given

sample of activity completion times, the project completion time equals the time to travel the longest path through the network. The longest path in this instance would commonly be called the "critical path".

1.0 *A General Synopsis of the Proposed Procedure*. The proposed approach to obtaining information on a project's completion time distribution involves the following five general steps:

Step 1. Identification: Represent the project and its component activities in terms of an acyclic network with one source and one sink. Identify each activity's completion time distribution or at least two percentiles of each activity's completion time distribution.

Step 2. Simplification: Replace various activity configurations and their associated completion time distributions by single equivalent activities and completion time distributions.

Step 3. Decomposition: Decompose the simplified network into several sub-networks by separating parallel sub-networks and then separating the resulting sub-networks at each cut vertex. A cut vertex is any node such that every path from the source to the sink passes through it.

Step 4. Analysis: Analyze each sub-network arising from Step 3 on the basis of two percentiles from each component activity's completion time distribution. The result of this analysis is an approximation of each sub-network's completion time distribution and the moments of this distribution.

Step 5. Synthesis: Combine the approximate sub-network completion time distributions determined in Step 4. The result is an approximate completion time distribution for the entire project.

2.0 *Simplifying the Initial Project Network*. Five activity configurations for which a single equivalent activity and completion time distribution are readily available are (1) two activi-

ties in series, (2) several activities in parallel, (3) five activities arranged in a "Wheatstone Bridge", (4) eight activities arranged in a "Double Wheatstone Bridge", and (5) seven activities arranged in a "Criss-Cross". These activity configurations are illustrated in Figure 1. The equivalent single activity completion time distributions for configurations 1-3 were originally identified by Hartley and Wortham [1] and for configurations 4-5 by Ringer [2].

3.0 *Analysis of a Sub-network*. The analytical procedure described in this section yields the following information on each sub-network when each component activity's completion time distrubition is replaced by a discrete two-point distribution with equal probability at each of two percentiles:

(a) upper and lower bounds on the mean sub-network completion time as well as the other moments of the sub-network completion time;

(b) upper and lower bounds on the distribution function of the sub-network completion time; and

(c) an approximate distribution function of the sub-network completion time.

The analysis of each sub-network involves essentially two parts:

1. The formation of "clusters" of activities whose effects on the sub-network completion time seem to be interrelated.

2. The approximation of the sub-network completion time distribution and moments on the basis of the clusters.

3.1 *Formation of Clusters*. The actual completion time distribution of each individual activity, A, in the sub-network is replaced by a discrete distribution with probability 1/2 at the lower percentile, ℓ_A, and 1/2 at the upper percentile, u_A. These will be sub-network completion time (a critical path time). The r-th moment of these 2^n times will be denoted by T_r, and the

distribution function of these times will be denoted by F. The approximation of the T_r's (especially T_1, the mean) and F is the goal of the subnetwork analysis. Since n will usually be fairly large, the complete enumeration of the 2^n critical path times will usually be unreasonably. Hence the activities which are most likely to be on the critical path through the subnetwork are identified and their joint behavior investigated.

The "mid-point" of the completion time distribution for activity A is defined to be $m_A = (\ell_A + u_A)/2$. The percentile difference $u_A - \ell_A$ is denoted by d_A and is assumed to be positive. The subnetwork's critical path when each activity's completion time is set equal to its mid-point will be referred to as the "original" critical path. The activities on this critical path will be referred to as "critical activities" with K equalling the number of such activities.

Some non-critical activities might become critical if some of the completion times for the original critical activities were decreased. These activities are identified as follows. The completion time for one critical activity, say A, is set equal to $\max\{m_A - \lambda d_A, 0\}$ where λ is a non-negative algorithm parameter which the user specifies. All other completion times are set equal to their mid-points. Then the longest path through the resulting network is determined. Any activities on this path which were not on the original critical path are now referred to as the "associates" of A since the effect of these "associates" on the networks' completion time is related to A's completion time. This procedure is repeated for each original critical activity.

Each critical activity and its associates make up one "cluster". These K initial clusters are now "pooled" by combining any two clusters with at least one activity in common. In general there will still be more than one cluster, and many of the n - K non-critical activities will not occur in any

cluster.

The associates correspond to the activities which become critical when the completion times of the original critical activities are lowered. However, some of the originally non-critical activities may also become critical if their completion times exceed their mid-points and the completion times of the original critical activities are at their mid-points. These activities are identified next. Each originally non-critical activity is investigated separately. If activity A is being investigated, then the completion time for A is set equal to $m_A + \theta d_A$ where θ is a non-negative algorithm parameter which the user specifies. The completion times for all other activities are set equal to their mid-points, and the corresponding critical path determined. This critical path will either be the original critical path or a new path which includes A. In the latter case, the activities on the original critical path which are <u>not</u> on the new critical path containing A are called the "eliminants" of A. Thus, the effect of A's eliminants on the networks completion time is related to the completion time for A. Hence, A is added to any cluster which contains at least one of A's eliminants. After this procedure has been repeated for each originally non-critical activity, the resultant clusters are "pooled" again by combining any two clusters with at least one activity in common.

Although the number of clusters is reduced when the pooling on the basis of the associates occurs and then further reduced when the pooling on the basis of the eliminants occurs, there will generally remain more than one cluster and several activities not in any cluster.

In general the larger the values of λ and θ the greater the number of activities in the clusters and the smaller the number of clusters. In particular the procedure for forming the clusters has the following properties:

Property 1: If $\lambda_2 > \lambda_1$, then any activity which would be an

associate of a critical activity A when $\lambda = \lambda_1$ would also be an associate of A when $\lambda = \lambda_2$.

Property 2: If $\theta_2 > \theta_1$, then any critical activity which would be an eliminant of a non-critical activity A when $\theta = \theta_1$ would also be an eliminant of A when $\theta = \theta_2$.

Property 3: For any originally non-critical activity A there exists θ_A such that A will have some eliminants for any $\theta \geq \theta_A$.

Property 4: For any fixed value of λ, the set of activities in the union of the clusters is monotonically non-decreasing as $\theta \to \infty$.

Property 5: There exists a finite value θ^* such that if $\theta \geq \theta^*$ then every activity would be in some cluster.

Property 6: The number of clusters, originally K, is non-increasing as $\theta \to \infty$.

Property 7: There exists a finite value θ^* such that if $\theta \geq \theta^*$, then there would only be one cluster.

Most of the properties of the cluster formation procedure are fairly straightforward; however, Property 7 requires some special justification. This justification is based on the following definition and theorem which is proven in Appendix A.

Definition: In any acyclic network a bridge over any two consecutive arcs A_1 and A_2 is any arc A_3 such that all paths from the source to the sink passing through A_3 do not pass through either A_1 or A_2.

Theorem 1: In any acyclic network with no cut vertices there is at least one bridge for any pair of consecutive arcs.

3.2 *Approximate Subnetwork Completion Time Moments and Distribution.*

3.2.1 *A Lower Bound on T_r.* For each cluster C let n_C denote the number of activities in C, and let $T_r^*(C)$ denote the average of the r-th power of the 2^{n_C} critical path times when

(a) the completion time for each activity not in C is equal to its mid-point, and

(b) the completion times for the activities in C are at each of the 2^{n_C} possible combinations of their upper and lower percentiles.

Let

$$T_r^-(\theta, \lambda) = \max_C T_r^*(C)$$

which depends on θ and λ since the composition and number of clusters depends on θ and λ.

The following two theorems are easily proven and are used in proving that $T_r^-(\theta, \lambda)$ is a lower bound for T_r.

Theorem 2: For any cluster C, any positive integer, and any activity A not in C,

$$T_r^*(C \cup \{A\}) \geq T_r^*(C) .$$

Theorem 3: For any two clusters C_1 and C_2 and any positive integer r,

$$T_r^*(C_1 \cup C_2) \geq \max\{T_r^*(C_1),\ T_r^*(C_2)\} .$$

Property 2 of the cluster formation procedure implies that if θ is increased the clusters expand or are pooled. Thus, Theorems 2 and 3 imply that, for fixed λ, $T_r^-(\theta, \lambda)$ is non-decreasing as θ increases. Furthermore, Properties 5 and 7 together imply that for θ sufficiently large there is only one cluster and all of subnetwork activities are in that cluster. Hence, for θ sufficiently large $T_r^-(\theta, \lambda) = T_r$, and the following theorem is true:

Theorem 4:

(a) $T_r^-(\theta, \lambda)$ is a non-decreasing function of θ for any fixed values of λ and r;

(b) there exists a finite value θ^* such that $\theta \geq \theta^*$ implies

$$T_r^-(\theta, \lambda) = T_r$$

for any λ, and r; and

(c) for any θ, λ, and r

$$T_r^-(\theta, \lambda) \le T_r.$$

3.2.2 *An Upper Bound on T_r and a Lower Bound on F.* Let $n_\cup$ denote the number of activities in the union of all the clusters, and let $T_r^+(\theta, \lambda)$ denote the average of the r-th power of the $2^{n_\cup}$ critical path times when

(a) the completion time for each activity not in the union of the clusters is equal to its upper percentile, and

(b) the completion times for the activities in the union of the clusters are at each of the $2^{n_\cup}$ possible combinations of their upper and lower percentiles.

An argument analogous to that used to prove Theorem 4 leads to the following result:

Theorem 5:

(a) $T_r^+(\theta, \lambda)$ is a non-increasing function of θ for any fixed values of λ and r;

(b) there exists a finite value θ^* such that $\theta \ge \theta^*$ implies

$$T_r^+(\theta, \lambda) = T_r$$

for any λ and r; and

(c) for any θ, λ, and r

$$T_r \le T_r^+(\theta, \lambda) \quad .$$

Let $F^-(\cdot;\theta, \lambda)$ denote the empirical distribution function of $2^{n_\cup}$ critical path times used to compute $T_r^+(\theta, \lambda)$. That is, let $F^-(t;\, \theta, \lambda)$ denote the proportion $2^{n_\cup}$ critical path times determined in the computation of the $T_r^+(\theta, \lambda)$'s that are less than or equal to t. Then, using Property 2, it follows that:

Theorem 6: For any values of λ and t, $F^-(t{:}\ \theta, \lambda)$ is a non-

decreasing function of θ.

Theorem 6 and Property 5 combined yield Theorem 7.

Theorem 7:

(a) There exists a finite value θ^* such that $\theta \geq \theta^*$ implies

$$F^-(t;\ \theta,\ \lambda) = F(t)$$

for every t and any λ; and

(b) for any θ, λ, and t

$$F^-(t;\ \theta,\ \lambda) \leq F(t) \quad .$$

3.2.3 *An Upper Bound on F*. Let $F^+(\cdot;\ \theta,\ \lambda)$ denote the empirical distribution function of the 2^{n_U} critical path times when

(a) the completion time for each activity not in the union of the clusters is equal to its lower percentile, and

(b) the completion times for the activities in the union of the clusters are at each of the 2^{n_U} possible combinations of their upper and lower percentiles.

An argument analogous to that used to prove Theorems 6 and 7 yields the following theorem:

Theorem 8:

(a) $F^+(t;\ \theta,\ \lambda)$ *is a non-increasing function of* θ *for every* t and any λ;

(b) there exists a finite value θ^* such that $\theta \geq \theta^*$ implies

$$F^+(t;\ \theta,\ \lambda) = F(t)$$

for every t and λ; and

(c) for any θ, λ, and t

$$F^+(t;\ \theta,\ \lambda) \geq F(t)$$

3.2.4 *Summary*. Theorems 2-8 together imply that for any value of Θ and λ chosen by the algorithm user:

(a) $T_r^-(\theta,\ \lambda) \leq T_r \leq T_r^+(\theta,\ \lambda)$, for any positive interger r; and

(b) $F^-(t;\ \theta,\ \lambda) \leq F(t) \leq F^+(t;\ \theta,\ \lambda)$ for any t.

They also imply that, for any r, λ, and t,

$$T_r^+(\theta,\ \lambda) - T_r^-(\theta,\ \lambda)$$

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and

$$F^{+}(t;\ \theta,\ \lambda) - F^{-}(t;\ \theta,\ \lambda)$$

would decrease monotonically to zero if θ were increased. In fact, Theorems 2-8 imply that there exists a value θ^* which doesn't depend on r, λ, or t such that $\theta \geq \theta^*$ implies that

$$T_r^{-}(\theta,\ \lambda) = T_r = T_r^{+}(\theta,\ \lambda)$$

and

$$F^{-}(t;\ \theta,\ \lambda) = F(t) = F^{*}(t;\ \theta,\ \lambda).$$

A reasonable approximation for F(t) is

$$F^{*}(t;\ \theta,\ \lambda) = 1/2[F^{-}(t;\ \theta,\ \lambda) + F^{+}(t;\ \theta,\ \lambda)]\ .$$

4.0 Synthesizing the Approximate Subnetwork Completion Time Distributions. When the original network is decomposed in Step 3, the result is a network of subnetworks with any two subnetworks either in series or in parallel. Let S_1 and S_2 be any two subnetworks, and let the corresponding approximate completion time distributions be denoted by F_1^* and F_2^*. If S_1 and S_2 are in series, then the completion time distribution for S_1 and S_2 combined is

$$\begin{aligned} F^{*}(t) &= \sum_{s \leq t} F_2^{*}(t-s)\ f_1^{*}(s) \\ &= \sum_{s \leq t} F_1^{*}(t-s)\ f_2^{*}(s)\ . \end{aligned} \tag{4.1}$$

where f_1^* and f_2^* are the discrete probability density functions corresponding to F_1^* and F_2^* respectively. If S_1 and S_2 are in parallel, then the completion time distribution for S_1 and S_2 combined is

$$F^{*}(t) = F_1^{*}(t) \cdot F_2^{*}(t)\ . \tag{4.2}$$

By repeatedly combining subnetworks that are either in series or in parallel, an approximate completion time distribution for the entire original network is obtained.

5.0 An Example. As an illustration of the general five-step

procedure introduced in section 2, the network in Figure 2 will be analyzed.

Assuming that at least two percentiles of each activity's completion time distribution have been identified, the following initial simplifications can be made:

(1) replace activities 1_1 - 1_5 (a Wheatstone Bridge) by a single activity, say 1_a;

(2) replace activities 1_6 - 1_{13} (a Double Wheatstone Bridge) by a single activity, say 1_b; and

(3) replace activities 1_{14} - 1_{20} (a Criss-Cross) by a single activity, say 1_c.

These initial simplifications lead to still further simplifications since the new activities 1_a and 1_b would be in parallel and hence could be replaced by a single activity, say 1_d; and then finally since 1_c and 1_d would be in series they too could be replaced by a single activity, say 1. The resulting simplified network is given in Figure 3.

The simplified network can be decomposed into the three subnetworks which are circles in Figure 3. For identification purposes, activities 1 - 5 will be called the first subnetwork, activities 6 - 16 the second subnetwork, and activities 17 - 30 the third subnetwork.

Using the methods described in section 3, the three subnetworks are analyzed <u>separately</u> on the basis of two percentiles from each activity's individual completion time distribution. Of course, these analyses depend upon the values of (θ, λ) specified by the investigator. The value of (θ, λ) need not be the same for all three subnetworks.

The three approximate subnetwork completion time distributions are then synthesized using (4.1) and (4.2). In particular, since the first and second subnetworks are in parallel, their respective completion time distributions can be combined using (4.2).

Then, since the combination of the first and second subnetworks is in series with the third subnetwork, the completion time distribution for the entire network can be found using (4.1).

6.0 Concluding Remarks. The proposed procedure for investigating the project completion time distribution involves five general steps: (1) Identification, (2) Simplification, (3) Decomposition, (4) Analysis, and (5) Synthesis. The necessity and value of these steps are obvious, and certainly the implementation of Steps 1, 2, 3 and 5 is straightforward. However, Step 4 involves several choices which merit some additional discussion.

The analysis of the network completion time is based on two percentiles of each activity's completion time distribution. Obviously the analyst would have more information to work with if he had each activity's entire completion time distribution, but such complete information is seldom available. Two percentiles are much more likely to be obtainable and therefore represent a compromise between the analyst's desires and practical reality. Furthermore several Monte Carlo investigations have suggested that essentially as much information can be gained using a reasonable pair of percentiles as could be obtained using every activity's entire completion time distribution. A "reasonable" choice for the pair of percentiles seems to be either (15, 85), (20, 80), or (25, 75). In fact, if the completion time distributions of the individual activities were independent normal distributions, then a choice of the 15-th and the 85-th percentiles would be roughly the mean minus one standard deviation and the mean plus one standard deviation, so that the means, variances, and covariances of the activities and paths would be the same using the two-point distributions as they would be using the entire distributions.

In the subnetwork analysis procedure the effect of the noncritical path activities is ascertained by letting their completion times be the mid-points of their upper and lower percentiles plus and minus θ times their percentile differences and by letting the completion times of the critical path activities be their

mid-points minus λ times their percentile differences. If the upper and lower percentiles were the 15-th and 85-th percentiles of a normal distribution, then the percentile difference would be approximately 2 standard deviations. Thus, θ and λ always refer to roughly "so many standard deviations". Hence it seems reasonable to only consider values of θ and λ in the interval [0, 3] and commonly less than 2. It is difficult to predict in general the cluster sizes for any particular values of θ and λ. (Of course as θ and λ increase, the cluster sizes increase as indicated by Properties 1-7 in Section 3.) On the other hand, it is not necessary to have large cluster sizes in order to obtain a reasonable approximation to the subnetwork's completion time distribution.

Although the cluster formation procedure considers activity completion times of the mid-point plus or minus θ or λ times the percentile difference, it could have also used plus or minus θ or λ times the standard deviation or any other indicator of the dispersion in the activity's completion time distribution. A modification of this type would not change the theoretical results given in Section 4 at all.

If the number of activities in a cluster, n_c, is moderately large, the number of percentile combinations, 2^{n_c}, to be considered is quite large. Since all the clusters are pooled into one cluster when the T_r^+'s, F^-, and F^+ are determined, the problem of a large value of 2^{n_c} may occur without (θ, λ) being unreasonably large. If this problem arises, a reasonable modification in the subnetwork analysis procedure is to evaluate only a random sample of the 2^{n_c} possible percentile combinations. Another modification in the subnetwork analysis procedure which may be made when the cluster sizes become large is the deletion of the calculation of F^+. This deletion is not unreasonable since the differences between F^- and F^+ are usually only very small even for small values of θ and λ. Furthermore what differences

there are appear almost entirely in the lower percentiles of F^- and F^+. When large clusters are involved, the deletion of F^+ will cut the computation time nearly in half.

There are several advantages to the proposed procedure over a simple Monte Carlo study of the project completion time. First, the simplification step usually makes a substantial reduction in the size of the project network - often a reduction exceeding 50%. Then the subnetwork analysis procedure provides information in terms of "associates" and "eliminants" about which activities play an important role in determining the subnetwork's completion time. This information also provides some indication of the effects of changing various activity completion time distributions. Furthermore, when the upper and lower bounds and other approximations are being obtained, the computational effort is concentrated on those activities which are most likely to affect the network's completion time distribution by only varying their completion times instead of unnecessarily varying all of the network's activity completion times.

Computer programs implementing the general procedure are available from R. L. Sielken Jr. These programs were written in Fortran IV and used on an IBM 360/65. The largest network analyzed thus far contained approximately 680 activities and 250 nodes.

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APPENDIX

Proof of Theorem 1

The networks considered in this appendix are assumed to be acyclic, have no cut vertices, and have one source and one sink. *Also the two arcs A_1 and A_2 are any two adjacent* (consecutive) arcs with A_1 preceding A_2.

Definition 1: A bridge over A_1 and A_2 is an arc, say A_3, such that all paths from the source to the sink passing through A_3 do not pass through either A_1 or A_2.

Definition 2: An origin violator of A_1 and A_2 is an arc, say A_3, such that there exists a path from the terminal node of A_1 to the sink which passes through A_3.

Definition 3: A terminal violator of A_1 and A_2 is an arc, say A_3, such that there exists a path from the source to the terminal node of A_1 which passes through A_3.

An intuitive feeling for these definitions can be obtained by considering Figure 4.

The following three lemmas are straightforward consequences of the definitions of a bridge, an origin violator, and a terminal violator.

Lemma 1: Every branch in the network is either a bridge over A_1 and A_2, an origin violator of A_1 and A_2, or a terminal violator of A_1 and A_2.

Lemma 2: A_1 is a terminal violator of A_1 and A_2, and A_2 is an origin violator of A_1 and A_2.

Lemma 3: Any arc A_3 cannot be both an origin violator of A_1 and A_2 and a terminal violator of A_1 and A_2.

Theorem 1: In any acyclic network with no cut vertices there is at least one bridge for any pair of consecutive arcs.

Proof of Theorem 1: Since the terminal node of A_1 cannot be a cut vertex, there exists a path P from the source to the sink which does not pass through the terminal node of A_1. Denote the arcs on P by $C_1, C_2, \ldots, C_p$ with C_{i-1} preceding C_i on P.

Suppose that none of $C_1, C_2, \ldots, C_p$ are bridges over A_1 and A_2. Then *Lemma 1 and Lemma 3 together imply that each of* $C_1, C_2, \ldots, C_p$ is either an origin violator of A_1 and A_2 or a terminal violator of A_1 and A_2 but not both. Since the origin node of C_1 is the source, C_1 cannot be an origin violator and must be a terminal violator. Similarly, since the terminal node of C_p is the sink, C_p cannot be a terminal violator and must be an origin violator. Hence, there exists $j \geq 1$ such that $C_1, C_2, \ldots, C_j$ are all terminal violators and C_{j+1} is an origin violator.

Since C_j is a terminal violator, there exists a path from the terminal node of C_j to the terminal node of A_1. Furthermore, since C_{j+1} is an origin violator, there is a path from the terminal node of A_1 to the origin node of C_{j+1} (the terminal node of C_j). These two paths imply the existence of a circuit from the terminal node of C_j to the terminal node of A_1 and then back to the terminal node of C_j. (The definition of P implies that the terminal node of C_j is not the terminal node of A_1.) This contradicts the given acyclic structure of the network and completes the proof of Theorem 1.

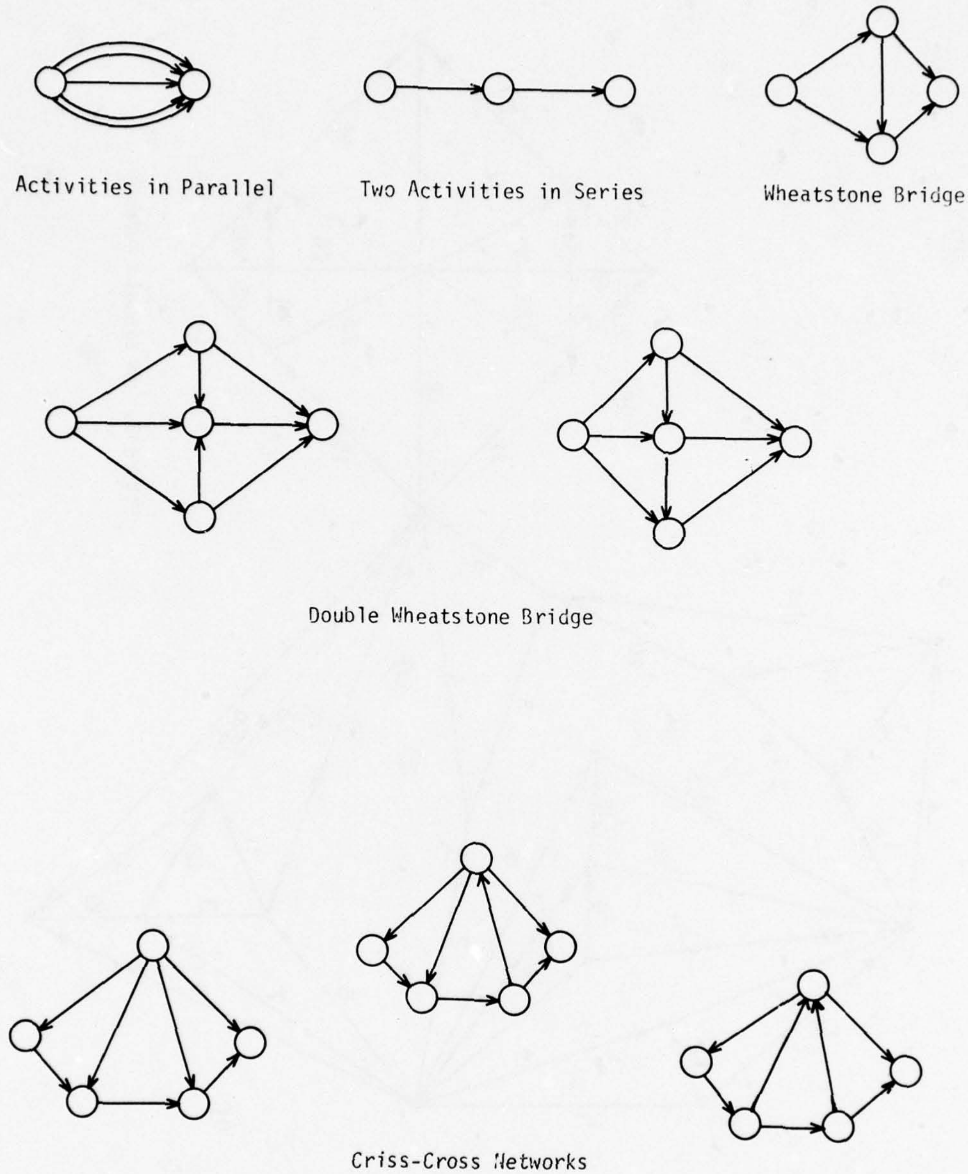


Figure 1. Activity configurations which can be simplified.

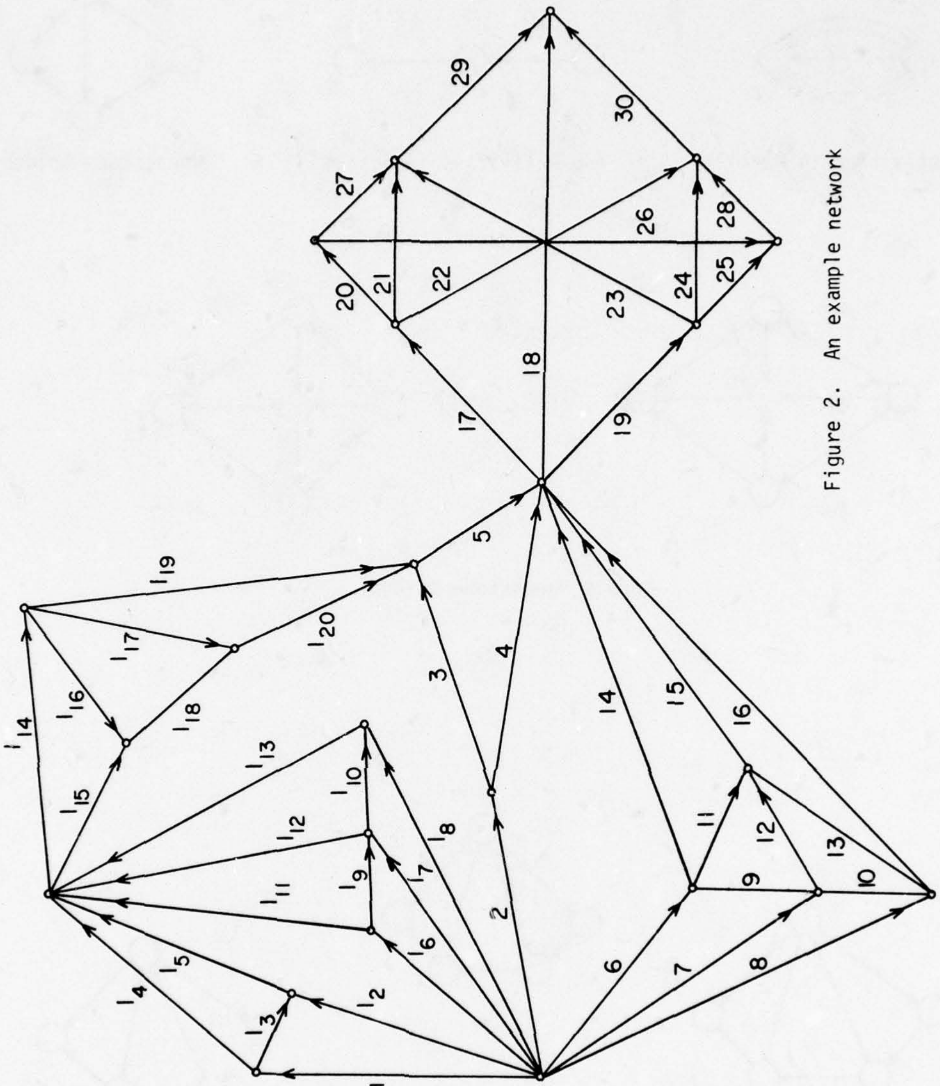


Figure 2. An example network

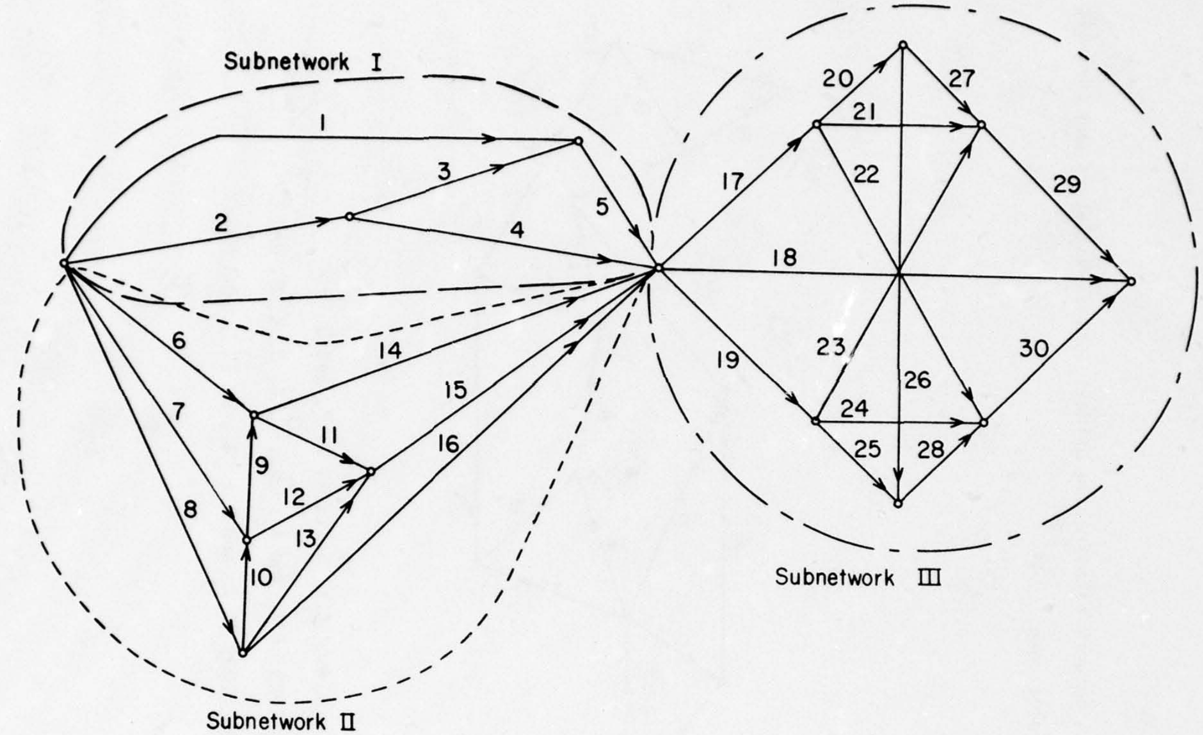
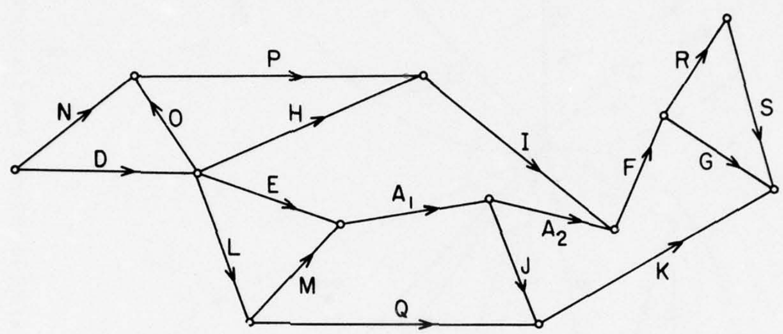


Figure 3. The simplified example network and its decomposition into three subnetworks.

Figure 4. A network illustrating bridges, origin violators and terminal violators.



BRIDGES over A_1 and A_2: H, I, N, O, P, and Q

ORIGIN VIOLATORS of A_1 and A_2: A_2, F, G, J, K, R, and S

TERMINAL VIOLATORS OF A_1 and A_2: A_1, D, E, L, and M

DISCUSSION

Question: I have a question for Dr. Hartley. I am trying, but I can't make much of a connection between the topic here which is the decision information for Command and Control and the interesting discussion of statistical PERT. I would solicit your observations based on the discussion given yesterday on how it might be applied. Would you please do that step in connecting the generalized work with the talk we had yesterday?

Hartley: I think all that I can tell you is that insofar as all these operations are part of C^3 maybe PERT is of some help for the auxillary operations providing the timing of equipment you require. That if you are, for example, using PERT operations for optimizing the activity in a theatre. But I will admit that I am not aware - maybe other people are - of any application that is directly concerned with oeprations or the ware position.

Question: It seems to me that the most appropriate theme is to maintain communications networks. Suppose we have a communications network with nodes, etc. It takes time - therefore the money - flowing from one node to another for communication needs. Generally we have two or three alternative networks or channels to bring the information you want in order to verify or, in the case of wartime, to obtain communications. Then I think there could be a way to estimate the final cost. This is the best connection I could make about communications.

Question: I guess a couple of things concern me about statistical PERT. In the first place it is basically an activity on those networks you didn't reflect any variation in branching logic. Do you have the capability to handle not only deterministic branching, but, probabilistic and conditional branching as well? That's question number one. The second question that I have: Can you handle different distribution types at nodes where your major time consumption is occurring?

Hartley: I will answer the first part because that is a problem

that does occur sometimes. If a particular operation in the future is not as yet decided upon, in particular how you are going to accomplish it, but you are still in the R&D stage of concluding the alternatives. Eventually you will make a decision. How you plan ahead under such an alternative? This is feasible, however, providing you are accepting the probability that this activity is carried out by Mode "A" or Mode "B". There's no problem about that. Your second question about what kind of distributions are we able to cope with. If we are lucky enough and data base is available for the distribution of the times to perform a particular operation then you can put in a numerical table. If, however, such an experience is lacking it is customary to use Beta distribution. I have to make it available for a limited number of alternatives.

Question: You mentioned about transitive models. As I understood it, you can get - in using the sequence of models a collection of models to solve problems, instead of one kind. It seems to me that it is just like a building being in operation. You're suggesting that it needs a few more rules. I think that is is just the philosophy that is missing here and maybe by complete submission he will come up with new tools and new approaches and better known abstractions. I don't disagree with anything you have said, but I don't think I said enough to give you the correct impression of what I do at the University. I am not saying there is no need for a succession models. I am just saying that given whatever decision you are looking at, one has to be prepared to use a variety of tools in the decision theory, for example, if one wants to look at optimal rules, the normal development has come to a halt in terms of what you can say. The mathematics stops you at a certain point. You can keep on writing equations down and you say well, I will keep on solving this equation - but that is not very useful to the practitioner. What I am saying is that context, for example, is that, to make headway, one has to go beyond that and say, how would this approximation behave in a

real environment where you don't know all the data? That means that you are not only involved in curve fitting techniques, you are involved in simulation of systems. So that what I am getting at is the inclination to make practical a lot of the model building ideas that have been around - perhaps new decision areas. The research scientist, as an applied mathematician, better not be an expert in just one avenue.

SOME PHILOSOPHICAL VIEWS ON ALGORITHMS AND COMPUTING METHODS IN APPLIED MATHEMATICS

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Abstract. This paper summarizes some of the work done by the Aero-Astronautics Group of Rice University in the area of numerical methods and computing methods. It describes some of the philosophical thoughts that have guided this work throughout the years. Recommendations are offered concerning allocation of funds and distribution of funds. Additional recommendations are offered in order to bridge the gap between the top management of government agencies and the academic community.

1.0 Introduction. Colonel Geesey, General Welch, Professor Thrall, Dr. Andrews, Ladies and Gentlemen:

Over the past several days, I have heard the terms C^2 and C^3 mentioned so many times by so many speakers that I cannot avoid the feeling of being an expert on the subject. Yet, was I an expert on the subject barely three days ago? Certainly not.

When I first glanced at the program and saw the symbols C^2 and C^3 repeated over and over, I thought: C^2 must denote some function which is continuous together with its first and second derivatives; analogously, C^3 must denote some function which is continuous together with its first, second, and third derivatives. Then, I thought: What are the military up to? Why are they interested in functions which might exhibit a discontinuity in the fourth derivative?

After listening to the opening speech of General Welch, it became apparent to me that the terms C^2 and C^3 were being employed in a context quite different from that familiar to pure and applied mathematicians. After glancing again at the program, I saw that one of the papers being presented had the title:

C^3 at Sea: A Commander's View. Then, I said to myself: perhaps C^3 denotes some new kind of periscope, or atomic submarine, or periscope mounted on some atomic submarine.

Obviously, not even my second interpretation was correct, and it took me a full day to establish a minimum of familiarity with the jargon of generals and admirals. Slowly, but surely, by the end of the day, I finally understood that C^2 means command and control and that C^3 means command, control, and communication.

2.0 Existence of a Gap. Allow me to look backward in time and glance panoramically at the content of this three-day meeting. After listening at the succession of presentations given by generals, admirals, professors, senior scientists, and various technical personnel, what is my overall feeling? Where do we stand now?

Somehow, I have the impression that there are two main possibilities: (a) perhaps, the wrong people were invited at this meeting; in that case, I am definitely one of the wrong people; or (b) perhaps, the right people were invited at this meeting; in that case, it seems apparent that a considerable gap exists between the top management of the military on one side and the academic people on the other side.

Under the assumption that interpretation (b) is correct, then the best thing which can be done at this moment is to make an effort in order to bridge the gap. With this in mind, I shall devote the rest of my lecture to presenting my philosophical views on research on algorithms and computing methods in applied mathematics. In particular, I shall focus my attention on the work of the Aero-Astronautics Group of Rice University. After this presentation is completed, then each of you can make up his mind as to whether (and to what degree) my work fits within the frame of a C^2-situation or a C^3-situation. While I am not so sure that my work is relevant to the C^2-point of view and/or the C^3-point of

view, nevertheless, there is little doubt in my mind that my work is relevant to AE (meaning aerospace engineering), ND (meaning national defense), and USA (meaning the United States of America).

3.0 Engineering Design. First, let me give you my background. I graduated in Aerospace Engineering from the University of Rome in 1946, and my initial intention was that of becoming a designer of all sorts of aerospace vehicles. Since the Italian industry was in total shambles in 1946 (we had lost the war), I accepted a job at the Military Aircraft Factory of Cordoba, Argentina. The director of the factory was Brigadier General I. San Martin, who had studied aerospace engineering in Italy at the Polytechnic of Turin, and who had a very soft spot in his heart for Italian technical personnel. He was affectionately called "El Petiso", meaning the short one, for obvious reasons.

As per my wishes, I was given several design assignments: first, the aerodynamic design of a propeller; next, the computation of the flight performance of a training plane; then, the complete preliminary design of a training plane. As my work in design progressed, I started to become aware of the tremendous limitations facing an aircraft designer: there were deadlines to be met and designs to be completed while employing very incomplete information. Early in the game (I was then only 25 years old), I decided that I did not like this state of affairs. I decided that incomplete information was unappealing to me and that, by temperament, I required more complete information. I felt that, in order to become a really good aircraft designer, a knowledge of advanced research techniques was necessary. With this in mind, I undertook a fateful (only for Miele, not for the rest of the world) and irreversible step toward basic research in aerospace engineering.

4.0 Engineering Research. My first love was flight mechanics. In 1947-48, the problems of the mechanics of flight of turbojet-powered vehicles were all important, and I devoted considerable time to the study in depth of flight trajectories. Within the class of feasible flight trajectories, the study of the optimum

flight trajectories is of particular importance, and this in turn leads to mathematical problems which belong to the realm of the calculus of variations and/or optimal control.

In 1952, the great and late Antonio Ferri offered me to join his research group at the Polytechnic Institute of Brooklyn. I accepted with enthusiasm and I worked with him for three years at the aerodynamic design of some of the hypersonic wind tunnels of the Polytechnic Institute of Brooklyn.

In 1955, I joined the staff of Purdue University, and returned to my first love (mechanics of flight), with a new twist: the study of the optimum trajectories of rocket-powered vehicles. I was fortunate enought to convince both AFOSR and NASA to back my work on optimum flight trajectories. In particular, I started a long and rewarding association with AFOSR.

In 1959, I joined the staff of the Boeing Scientific Research Laboratories and continued my work on optimum flight trajectories. This work culminated in the book Flight Mechanics (Addison-Wesley, 1962). In addition, I became interested in the theory of optimum aerodynamic shapes. Together with my research group at BSRL, I tackled a wide variety of optimization problems occurring in the aerodynamics of supersonic, hypersonic, and free-molecular flows. Mathematically speaking, these problems also belong to the realm of the calculus of variations and/or optimal control.

In 1964, I decided that it was time to return to university teaching and research. The combination of Houston with Rice University proved to be particularly attractive, also in view of the fact that the NASA-Johnson Space Center is located in Houston. At Rice University, I continued aggressively my work on optimum aerodynamic shapes under the sponsorship of AFOSR and NASA-Langley Research Center. This work culminated in the edited book Theory of Optimum Aerodynamic Shapes (Academic Press, 1965).

5.0 *Applied Mathematics Research.* About 10 years ago, while working on the problem of optimizing wings, fuselages, and wing-fuselage combinations under different flow regimes, our research program reached a point where advances became increasingly difficult. My feeling was that we were in the presence of a rather steep wall and that a tremendous amount of analytical ingenuity was required in order to make relatively small advances. Perhaps, the best way to portray the situation is this: I felt like a man who is trying to walk on broken glass without shoes.

The reason for the changed situation was the following. We had almost exhausted our bag of analytical tricks, and we were facing numerical difficulties of ever increasing complexity. When I sensed that this was the case, I said to myself: Angelo, you can no longer be a first-rate engineer without a full and total knowledge of numerical methods. With this in mind, I undertook another fateful (again, only for Miele, not for the rest of the world) and perhaps irreversible step toward basic research in numerical methods and computing techniques.

Since I felt that to work simultaneously on engineering research and mathematical research was rather inefficient (any good general would understand that), I dumped overnight all of my engineering problems and started to work at full blast on mathematical problems only. My intention was to gain rapid knowledge of numerical techniques, in order to be able to return to engineering at a later time and then tackle more complex problems.

In the meanwhile, Mr. R. L. Pritchard, formerly of the Boeing Company, had joined my group at Rice University. Together with him, I undertook a review of previous work in the area of algorithms for optimal control theory. As soon as we started this review, we realized that we faced two severe limitations. First, the work of some of the leading authorities on the subject was not exactly a masterpiece of clarity. Second, there were some huge holes in the existing body of knowledge; and there were unanswered questions all over the place.

In the light of this situation, we decided early in the game that we should develop our own independent research program, leading to new algorithms for solving all sorts of problems of applied mathematics on a digital computer. Since I could bank on my previous reputation in engineering research, it was not difficult for me to persuade AFOSR, NASA, and later on NSF to back the work of the Aero-Astronautics Group of Rice University in the area of numerical methods.

As soon as our program on algorithms for optimal control theory had started, I realized that the solution of optimal control problems on a digital computer cannot be divorced from the solution of differential equations. That being the case, we started a second program dealing with the numerical solution of two-point and multi-point boundary-value problems on a digital computer.

For several years, the computing center of Rice University had been equipped with a Burroughs 5500 computer; more recently, it has been equipped with an IBM 370/155 computer. In spite of the considerable capabilities of these computers, we found that some optimal control problem could tax the memory of these computers almost to the limit. We also found that some optimal control problem could be quite expensive on a digital computer. Since our funds were relatively limited, it seemed difficult for us to be able to develop in this way the type of systematic information which is needed in order to give algorithms for optimal control theory their most useful structure.

To offset the above difficulty, I reasoned as follows. For every problem of optimal control, there must be a counterpart in mathematical programming which is easier to solve: it does not test the memory capabilities of a given computer, and it does not require as much computer time. In this spirit, we started a third program leading to the development of computer algorithms for mathematical programming problems.

Just as the solution of optimal control problems is related to the solution of differential equations, the solution of mathematical programming problems is related to the solution of nondifferential equations (namely, algebraic and transcendental equations). As a consequence, it was natural for us to start a fourth program dealing with the numerical solution of nondifferential equations.

In summary, after a few short years, our research program on computing methods had grown to a considerable size. Indeed, it included calculus of variations, optimal control, differential equations, two-point and multi-point boundary-value problems, mathematical programming, and solution of nondifferential equations. Several people have contributed in a substantial way to this program. While the list is a long one, I would like to mention Professor H. Y. Huang (presently with EPRA, Exxon Production Research Company, Houston, Texas) and Dr. A. V. Levy (presently with CIMAS, Computing Center of the University of Mexico, Mexico City, Mexico).

6.0 Thoughts on Algorithm Development and Usage. In Section 5, I discussed the natural development of our research program on computing methods. In this section, I shall describe some of the philosophical thoughts that helped shaping our program.

(a) First of all, the nature of a digital computer is such that the use of vectors and matrices is beneficial to problem formulation. On a digital computer, a problem of flight mechanics is no different from a problem of chemical engineering, as long as both problems are described by the same kind of vector differential equation and vector boundary conditions, for example,

$$\dot{x} - f(x,t) = 0, \qquad 0 \leq t \leq 1, \tag{1}$$

$$g(x,t) = 0 \qquad \text{at } t = 0, \tag{2}$$

$$h(x,t) = 0 \qquad \text{at } t = 1, \tag{3}$$

where f,g,h are vector functions of appropriate dimensions.

This concept helps grouping some apparently different problems into broad classes of problems, such that a common algorithm

can be developed for solving every problem belonging to the same class. The fact that a particular problem deals with flight mechanics and another particular problem deals with chemical engineering comes into play only a posteriori, after an algorithm has been developed, through different specialization of the functions f,g,h and their derivatives.

If the above point of view is taken, then one can develop algorithms useful for a wide variety of problems of the real world, even though the primary interest of a particular scientist might be just flight mechanics. Indeed, by giving generality to problem formulation, one can succeed in developing algorithms not only useful in aerospace engineering, but also simultaneously useful in other areas of engineering, science, and economics.

(b) In line with (a), it is simply uneconomical and inefficient to try to develop a new mathematical algorithm every time one faces a new technical problem. Usually, it is more economical and efficient to try to employ transformation techniques such that a problem A belonging to a given class, for which algorithms are not available, is converted into a problem B belonging to another class, for which algorithms are already available.

Of course, transformation techniques have their own limitations. They can be used providing the structure of problem B is not too different from the structure of problem A. With these limitations in mind, judicious use of transformation techniques can be helpful in limiting to a considerable degree the proliferation of algorithms solving similar and/or related problems.

(c) The successful development of algorithms for digital computer usage is partly a science and partly an art. Computer experimentation plays a fundamental role, since this is the only way to uncover possible weaknesses and correct these weaknesses if they exist. Only in this way can one hope to develop algorithms that are robust, that is, capable of leading to the solution of many different problems under a wide variety of operating conditions.

(d) As a corollary to the above thought, it is rather unlikely that a successful algorithm might be developed by some mad scientist, who gets up on a given morning on the right side of the bed. It is nice to dream of some genius who had a wild idea that just happened to work without a hitch on a digital computer. But frankly, this is not the standard situation; and this is because a digital computer has its own rules of operations and its own internal logic; and while this logic is limited, it is usually more consistent than our own human logic.

(e) A scientist has the duty to test his theories experimentally, in order to understand its limitations and try to offset these limitations, if at all possible. If this is not possible, then a scientist has the duty to state these limitations clearly, so that they can be corrected through subsequent work of the same group of people or some other group of people.

(f) Frank exchange of information, collaboration, and interaction between scientists belonging to the same group is fundamental in order to succeed in algorithm research and development. It is most important that both information relative to failures and information relative to successes be conveyed promptly to every element in a group. Indeed, negative information can be as important as positive information in shaping the long-range goals of a group and in determining the most efficient distribution of tasks within a given group.

(g) When applying optimization algorithms to the solution of engineering problems, it must be remembered that nothing catastrophic usually happens, from the point of view of the performance index, if an exact optimum is replaced by an approximate optimum. This is the same as saying that, in the real world, satisfaction of the feasibility equations is usually more important than satisfaction of the optimality conditions.

Paradoxically, it might seem that I am stating that optimization is less important than we like to think, and this thought might shock some professional optimizers. But, if one recovers

from the shock, then one can take advantage of this thought when selecting the algorithm to be employed in the solution of a given engineering problem and when choosing the so-called stopping conditions for the feasibility equations and the optimality conditions.

By adhering to the point of view expressed under points (a) through (g), the Aero-Astronautics Group of Rice University has succeeded in developing a wide variety of robust algorithms useful for all sorts of problems of applied mathematics. Perhaps, the best measure of this success is the fact that our group has received over the years some 5000 requests for the various reports and papers that summarize the results of our research program. Does this mean that the proof of the pudding lies in the eating?

7.0 A View of the Future. Allocation of Funds. Even though the digital computer is barely 20-25 years old, considerable advances have been achieved thus far in the science and art of computing. It appears probable that these advances will continue without any substantial slackening over the next 25-30 years. It also appears probable that, by the beginning of the next century, a relative steep wall might be reached. Beyond that time, progresses might become slower and more painful to achieve.

Since the next 25-30 years appear to be crucial to the development of new and more sophisticated computing techniques, the following questions arise: (i) Should allocations for research in computing methods be increased? (ii) What is the proper level of support?

In approaching the above questions, the proper reasoning is as follows. Basic research in numerical methods and computing techniques transcends in importance basic research in every other area of engineering, science, and economics, for a simple reason. Real-world problems of aerospace engineering, electrical engineering, mechanical engineering, and so on, ultimately require that some set of equations and/or inequalities be solved on a digital computer. Therefore, to acquire a capability in numerical methods

and computing techniques implies to acquire an enhanced capability in engineering, science, and economics.

In the light of the above reasoning, it appears that the answer to question (i) is decisively affirmative. Concerning question (ii), one must remember that research in computing methods is relatively inexpensive and occupies at this moment only a tiny fraction of the overall budget of major government agencies, such as AFOSR, ARO, ONR, and NSF. Thus, it is entirely appropriate for the top management of the military as well as for the top management of NSF to consider doubling or tripling the funds presently allocated for computing research.

8.0 Distribution of Funds. In this section, I shall touch a very sensitive topic, that of the distribution of research funds within the nation. The standard operating procedure of government agencies seems to be more or less as follows. Suppose that government agency XYZ has a yearly budget of 2000K. Furthermore, suppose that we divide this budget into 100 equal packages, each worth 20K. Then, it follows that government agency XYZ can support 100 principal investigators, spread more or less with uniform density all over the country.[1]

In proceeding along the above lines, government agency XYZ avoids political criticism. At the same time, it buys technical insurance: if agency XYZ supports 100 efforts, even admitting that only 20% of these efforts turn out to be good, then agency XYZ is actually supporting 20 good research programs.

The drawback of the above operating procedure is that it is in direct conflict with two basic concepts of the real world: (i) even though the USA is the richest nation in the world, its financial means are limited; and (ii) in any given area of research, the supply of true talent is also quite limited.

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[1] In the C^1-language (C^1 meaning contracts), it is known that 1K = $1000.

Because of the realities of (i) and (ii), one must wonder whether a more efficient use of national resources can be achieved through concentration of effort, that is, through the allocation of larger grants into more capable hands. In suggesting this course of action, I feel that some immediate clarification is necessary. I am not really thinking about semipolitical handouts of the Themis type. I am rather thinking about allocation of larger chunks of research funds into the hands of the best available technical talent.

Now, I am fully aware of the fact that allocation of research funds solely on the basis of technical considerations might cause a national outcry: I can envision scores of senators and congressmen firing telegrams all over the place, because their pet university did not get the proper share of the research pie.

In the light of the above possibility, it might be that the best course of action is a compromise between national needs and local needs. As the Romans used to say, <u>in medio stat virtus</u>. For example, consider once more the budget of government agency XYZ (2000K), and suppose that this budget is split into two equal parts: 1000K devoted to the support of small efforts (each worth 20K) and 1000K devoted to the support of large efforts (each worth 100 K). If this course of action is taken, then government agency XYZ might be supporting 50 small research efforts plus 10 large research efforts. In this way, political criticism might still be avoided; technical insurance might still be bought. Yet, the realities of the financial situation of the country and of the nature of basic research might be more adequately considered than ever before.

9.0 Lagrange and Napoleon. During the first day of this meeting, General Welch mentioned a particular technical problem in which Lagrange multipliers played a role. I would like to inform General Welch that I have been dealing with Lagrange multipliers for the past 30 years. At Rice University, we have developed all sorts of algorithms, even algorithms capable of optimizing the distribution

of Lagrange multipliers withing a system governed by equations and or inequalities. Also, we have optimized the distribution of Lagrange multipliers for systems described by differential equations and appropriate boundary conditions.

The name Lagrange is of such common usage in today's technical world that a comment is in order. Contrary to superficial appearance, Lagrange was neither a French nor a Louisiana Cajun. He was an Italian, born in Turin in the year 1736. Indeed, his certificate of birth bears the name of Giuseppe Lodovico Lagrangia. He taught ballistics at the Military Academy of Artillery in Turin and founded the Academy of Sciences of Turin, a dusty academy that still exists today. By the way, I was just elected a Corresponding Member of that venerable academy.

At the age of 30, Lagrangia (already famous for his work on Analysis, Algebra, Calculus of Variations, and Analytical Mechanics) left Turin, first for Germany (where he spent 21 years) and then for France (where he spent the last 26 years of his life). In France, he changed the spelling of his name to Lagrange, and this explains why we talk today about Lagrange multipliers rather than Lagrangia multipliers.

But Lagrange was not the only Italian who became prominent in the French-speaking world. Since this is a meeting of generals, I would like to mention the name of the greatest general of all times, Napoleone Bonaparte, who was born in Aiaccio, Corsica, from an Italian family.

It is not ironic that the two greatest Frenchmen that ever lived, Lagrange and Napoleon, both happened to be Italians?

10.0 Concluding Remarks. I have done my best to give everybody in this audience an idea about the nature of the work of the Aero-Astronautics Group of Rice University in engineering and applied mathematics. I have described some of the philosophical thoughts guiding our work in numerical analysis and computing methods.

I realize that our academic work has become so technical that, quite often, people in government agencies are at a loss in

understanding the implications of this work. This leads to the gap that I have described at the beginning of my talk.

To bridge this gap, it would be a good idea that government personnel (in particular, AF personnel) be sent to work with senior scientific personnel, working in the universities, for a period of one-two years. In this sense, I support the recommendations provided by Professor R. E. Kalaba in the opening lecture of this session.

Concerning the relation of my work with C^2-situations and C^3-situations, I cannot tell for sure whether a connection exists. But I can think of two problems to which my work applies and which should be important to the top management of the military: weapons allocation problems and interception problems. At any rate, while I am not sure of the relevance of my work to C^2 and C^3, I am quite sure of its relevance to AE, ND, and USA.

Now, suppose that there is somebody in this audience who is still not satisfied with my statements and says: "Dr. Miele, I like your speech, but I still do not understand the relation of your work with C^2 and C^3". Then, my answer would be more or less as follows: "Mr. so and so, I believe that your question is very perceptive and stimulating. But I am unable to supply a clear-cut answer, for reasons of national security. Specifically, in order to expound about the relations of my work with C^2 and C^3, I would have first to expound about the relations of my work with C^4 and C^5. And this I cannot do, because it is militarily classified information".

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A COMMENT ON THE ESTIMATION OF PROBABILITY DENSITY FUNCTIONS

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Decision theory and general statistical models are currently being applied in many military settings. For example, consider the situation in which it is desired to discriminate between whales and submarines. Or, as another example, consider the situation in which it is desired to detect the presence of an aircraft. These and other similar situations can be modeled as hypothesis testing problems.

In a vast number of decision theoretic models, there is the assumption of a probability density function which characterizes the distribution of the observed quantities. The resulting hypothesis test is then structured upon the assumed probability density functions. By and large, probability densities are not obtained from physical derivations, but from emperical data.

Measurements are taken, and from these measurements a density function is obtained. Several methods have been proposed for the estimation of probability density functions, and numerous properties of these methods have been studied [1]. Perhaps the most common method is that which is based upon the "kernel approach" to the estimation of probability density functions. However, these methods assume that the measurements from which the density is estimated are not corrupted by noise.

In many practical situations, the measurements from which one constructs the estimated density are corrupted by noise. The corrupting noise might arise from background noise not associated with the random variable of interest, or it may arise from noise introduced by the measuring techniques. The author is currently investigating the (nonparametric) estimation of a probability density function from noisy measurements. Several classes of noise

distributions are being considered. The method is based upon the "kernel approach" to estimation of probability density functions introduced by Parzen. His basic technique is modified with a type of de-convolution operation. The goal is the design of practical (i.e. easily implementable) estimators which are asymptotically unbiased and consistent in the quadratic mean. Although there is a quite extensive literature on the estimation of probability density function (most of it relatively new), little has been done for the case where the measurements are corrupted by noise.

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III. MILITARY APPLICATIONS

HUMAN PROCESSES IN BATTLEFIELD INFORMATION SYSTEMS

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The vehicles for decision information for tactical command and control from an Army perspective are often identified as battlefield information systems. For the forseeable future, human processes will be an integral part of such systems and must be attended to as explicitly as the computer technology if significant advances in system capability are to be achieved. This concept and its implications will be developed in subsequent sections of this paper. We will begin with an attempt to define the Army problem and then consider in sequence what are some of the relevant variables, how their effects might be measured, whether solutions are intuitively obvious, and some of the promises to be realized and pitfalls to be avoided as we look towards advanced computer technology to provide solutions.

1.0 Scoping the Army Problem. A convenient point of departure for looking at Army concerns within the workshop theme of "decision information for tactical command and control" is to provide an operational definition or statement of the goals or objectives of command and control. Simply stated command and control is the planning, direction, coordination and control of operational activities of forces in a manner most likely to result in the achievement of friendly objectives and the denial of competing objectives to the enemy. Requisite for effectiveness in this domain is the availability of required information in a suitable form, on a timely basis, appropriately digested and synthesized to enable the best decision, monitoring the execution of the decision, and reacting ad hoc to unexpected happenings in the subsequent unfolding events. It is clear that this is no small order given the tempo of modern wearfare and the diversity of kinds, enormity

of amounts and sources of information and means to acquire same. It is also relevant to note in this context that an Army division is by no means small business either in terms of capital investment, recurring costs or numbers of personnel "employed". It can be seen in Table 1 that the initial fielding costs approach $2 billion for an armored division and only about $200 million less for a mechanized infantry division. This translates into roughly 10 to 12 billion dollars for a Corps and more than one-quarter million personnel.

Table 1. Approximate Magnitude of Resources "Commanded" and "Controlled" by an Army Division and Corps

	FORCE COSTS (WAR CONDITIONS				
	INITIAL FIELDING COST	ANNUAL RECUR COST	OFF STRENGTH	ENLISTED STRENGTH	TOTAL PERSONNEL
CORPS		APPROX 5.5 X DIV			
MECH INF DIV (FORCE EQUIV)	1.699 BIL	796 MIL	3,979	42,008	45,987
ARMORED DIV (FORCE EQUIV)	1.878 BIL	840 MIL	4,173	43,557	47,730

Achieving a command and control capability to cope with the highly complex dynamics of future battlefield situations is a high priority need. Satisfaction of this need must focus on affordable alternatives which capitalize on the respective strengths of man and computer and compensate for their respective weaknesses. An initial step in such a procedure is to determine what variables are relevant.

2.0 Some Relevant Variables. The effectiveness of most any system can be attributed to three major factors which are at one and the same time both independent and interdependent to varying degrees depending on the purpose the system is intended to satisfy. This can be expressed analytically as:

$$E = F(S, P, D)$$

where E = potential battlefield effectiveness as a function of:

S = System design capability

P = Proficiency of operators and users of the system

D = Doctrine for employing/utilizing the system

The distinction among these factors is particularly important when it comes to considerations of designing a system around human limitations i.e. there is no point in providing a sophisticated system capability the utilization of which is dependent upon a skill level which doesn't exist or can't be trained into the expected user. Conversely it is not efficient to provide for extensive user training for executing functions which could easily be accommodated in system design capability. There are many trade-offs which can be made in this domain. Failure to perform the research necessary to support these determinations is likely to result in overdesigned or underdesigned hardware, over trained or under trained users and unutilized or inefficiently utilized systems.

There are many variables or issues which impact on the principle factors and related tradeoffs associated with battlefield information systems. A number of the more significant ones which clearly involve human processes and performance are identified and their implications briefly described below:

1. Volume of information. The amount of information potentially available is so enormous that it may well impede rather than aid unless effective means can be developed to screen out irrelevant, redundant information; codify and catalog for ready accessibility; aggregate and integrate for data base economy and understanding; identify and purge that data which is of least current and projected value.

2. Quality of information. The quality is highly variable as a function of the source, inherent situational uncertainties, coding, transformation and inputting errors. Ways must be found to minimize occurrence of errors, detect errors when they do occur,

and accurately assess and communicate the probable accuracy of the information.

3. Value of information. Worth is variable as a function of echelon, mission and timeliness as well as quality characteristics. Ways must be found for realistically assessing the expected value of information, and establishing processing and acquisition priorities in accordance with the value structure.

4. Manipulation of information. In a problem solving sense data manipulation is essential if our capability is to be more than a file cabinet and message switching operation coupled to a user's unaided decision process. Man's capability must be extended with models, algorithms, logic structures, etc., to enable him to more quickly, thoroughly and accurately consider, evaluate and interpret the masses of information and myriad complexities involved in various alternative actions.

5. Form of information presentation. Form is key to efficient understanding, assimilation and utilization of information. Not enough is known about the perceptual-cognitive domain, symbolic representation and differentiation, sensory overload, etc., as a function of information characteristics and intended use to enable sound decisions regarding questions of presentation media, sensory modality, graphic vs. alpha-numerics, black and white vs. color, shape vs. size, etc., in general. Cultural and task differences need also be addressed.

6. Communication of information. Communication is a sine qua non of effective information systems and is the single varible having the greatest discrepancy between the actual severity of the problem and the acknowledged severity. It encompasses man/man, man/machine, and machine/machine (interoperability) exchanges. It relates to the penennial problem wherein the exchange of words, shapes, sentences, codes, etc., is not accompanied by an exchange in the intended meaning.

7. Factors underlying command team effectiveness. Most command and control research and training vehicles now focus on the procedural aspects of the tasks to the neglect of factors less readily defined. Research is required to identify the less obvious variables that are reliably related to operationally defined dependent variables and to develop a body of knowledge for such independent-dependent variable relationships, and the interactions across classes of variables. Major factors are probably going to be in the general areas of information processing capability of the command team, the team decision-making process employed and the structural relationship among members of the command team.

8. Decision making strategies. This area differs from information processing in that the strategies of commanders or unit heads probably concern more the type of information used for decisions, and the manner in which available processed information is used in the decision-making process. There obviously is an interaction between the decision styles of "heads" and the organization's structure. Some structures, from a methodological viewpoint make it extremely difficult to ascertain what information entered into the forming of the decision. In some structures the relative balance of policy vs. data-type information from external and internal environments may be different from the balance found in other structures. (That is, the conventional line-staff structure has different functional properties from, say, a lattice structure.) The quality of decisions and the strategies for decision-making may depend on that type of balance, among other factors. The utility of investigating differences in decision strategy stems from the potential payoff for such knowledge for application to training.

9. Role separation between commander and staff. Maximizing the effectiveness of command and control teams probably requires - as the literature seems to suggest - a separation of responsibility

for routine (primarily procedural) and non-routine tasks. While such separation occurs now to varying degrees the demarcation is often less than crystal clear and more than a little bit arbitrary. Perhaps this is because the routine - non-routine dimension is often less of a dichotomy and more of a continuum than is usually imagined. Figure 1 is a schematic of the major functions or processes occurring in the tactical operations center of an army division or corps which portrays such a dichotomy in terms of "rule-followers" and "rule makers". While this is a convenient way of conceptualizing a major functional difference particularly from a point of view of defining manageable, meaningful research chunks, it too is arbitrary and the dichotomy may be more apparent than real depending on ther personages involved in these functions. Also related to this issue is the question of centralization/decentralization of responsiblity and authority. The transition from reasonable delegation to micro management is made all the more tempting by the availability of automated information systems.

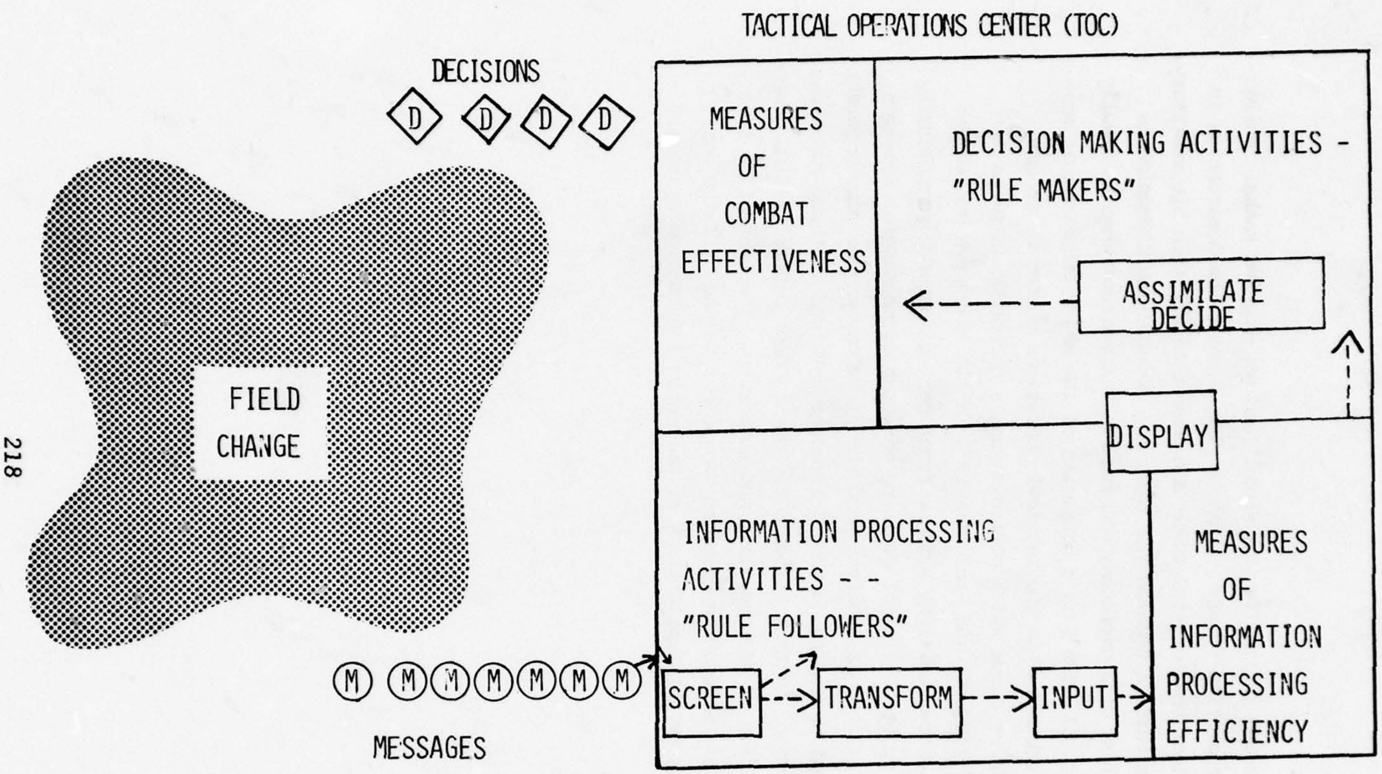

FIGURE 1. SCHEMATIC OF MAJOR PROCESSES AND PERFORMANCE MEASURES IN A TOC.

If further "noise" were needed in our attempts to better understand the influence of the above variables and issues then we are in luck because most of the above are in some way affected by a host of environmental, psychological and sociological factors, e.g., stress, motivation, fatique etc. Introduction, control, manipulation and measurement of such factors for experimental purposes within the broader context of command and control is at best exceedingly difficult and in many instances not justifiable in a risk/benefit analysis. Whatever variables are investigated, the research can be no better than the criteria and measures of performance or effectiveness. Accordingly some of the considerations and problems involved in determining what should be measured, how it should be measured and how one can interpret the outcome will next be discussed.

3.0 Measurement. The answers one gets to questions of role, importance and interactions of the numerous variables which might be influencing the effectiveness of command and control functions and systems is very much dependent upon what is measured, the circumstance of its measurement and the scoring or weighting of the outcomes. While there are many lessons that can be learned from actual war time operations, there are many reasons too obvious to discuss why research should not and cannot depend on availability of such circumstances. For battlefield information systems at least, this means some sort of abstraction or simulation of the real world. The key element in such a procedure is to insure that sufficient fidelity to the real world is retained that you have confidence in the outcome at least in terms of the relative order of alternatives and that sufficient control can be exercised to allow attribution of effects to specific variables or their combinations.

A man-in-the-loop interactive simulation is used at the Army Research Institute as one vehicle for the development and empirical evaluation of man/procedure/equipment alternatives. This vehicle or research tool is called SIMTOS which stands for Simu-

lated Tactical Operations System. Its resemblance to any specific Tactical Operations System past, present or future in terms of hardware or software design concepts in at most superficial. It does attempt a reasonable incorporation of the peopleware factor and allows representation of the functions, interfaces, and information content which would characterize a TOS. Figure 2 identifies the principle components of the simulation and the play options. A more detailed description is available for anyone interested [2]. Not all variables can or perhaps should be included in the system simulation. A frequently used approach is analogous to that of Spaulding et al [8] learning. In the research setting a small subset of variables or processes may be investigated in a tactical problem slice which allows a better understanding of the underlying dynamics and sensitivities. Gradually that which shows greatest promise becomes integrated with other substructures and ultimately is scrutinized in the full simulation.

MAN-IN-LOOP DIVISION LEVEL SIMULATION

COMPONENTS:

- SCENARIO
- INPUT/OUTPUT DEVICES
- COMPUTERIZED DATA BASE
- TASKING
- PERFORMANCE MEASUREMENT

FOR DEVELOPMENT AND EMPIRICAL EVALUATION OF MAN/PROCEDURE/EQUIPMENT ALTERNATIVES

OPTIONS:

- G-2 STAND-ALONE
- G-3 STAND-ALONE
- G-3/G-2 COMBINED PLAY
- TWO SIDED PLAY

FIGURE 2. CHARACTERISTICS, COMPONENTS AND PLAYER OPTIONS IN SIMTOS

But what measures of performance should one use? Other things being equal we tend to feel most comportable with objectively determined numbers but it depends on what is being measured whether such quantification is feasible and what the unit of measurement should be. Referring back to Figure 1 you will see that a distinction is made between the information processing activities and the decision making activities. In the former, measures of information processing efficiency are indicated. These typically include speed, accuracy, completeness, etc. This seems straight forward enough but since frequently we can improve accuracy at the expense of completeness or vice versa and either might be improved at the expense of time, trade offs must be explicitly considered and perhaps a variable weighting scheme derived. At this point we find a need to go to the next higher functional level where hopefully we can assess the importance of these measures in terms of their impact on decision making activities. But what measures of effectiveness do we use to evaluate decision behaviors?

Initially in SIMTOS performance was evaluated against "school solutions" generated from the collective judgement of military experts. Such criteria have merit in terms of being obtainable when other more objective measures are not and frequently prove less costly than developing the means to assess performance in terms of what was won and lost. With the addition of appropriate engagement tables, accounting routines etc. to SIMTOS it is now customary to assess outcomes in terms of measures shown in Figure 3. A word of caution is in order here. Less than optimum and even wrong decisions can result in favorable outcomes. This is as true in every day life as it is in tactical simulations. Accordingly it can be of value to recover data which will allow an interpretaion of outcomes in light of deviations of behavior at decision nodes from that of the school solution. Even given the measures of Figure 3, it requires no special genius to recognize that the weighting problem has not been obviated.

SIMTOS SCORING CRITERIA

MEASURE	REMARKS
TERRITORY	LOST, GAINED, CONTROLLED
TIME	TO ACCOMPLISH MISSION
FRIENDLY	NUMBER OF PERSONNEL, EQUIPMENT, SUPPLIES
ENEMY ATTRITION	NUMBER OF PERSONNEL, EQUIPMENT, SUPPLIES
RESOURCES EXPENDED	AMOUNT OF AMMO, AIR SORTIES, ETC.
FORCE READINESS LEVEL	% PERSONNEL, EQUIPMENT BASIC LOAD AVAILABLE UPON COMPLETION OF BASIC MISSION

Figure 3. Scoring Criteria Used in Assessing Outcomes of SIMTOS Play.

At this point one might wonder if empiricism is worth the effort. Probably much of what we learn is logically or intuitively obvious and what isn't is determinable by asking knowledgeable users. This notion will now be examined a bit more closely.

4.0 Some Anomalous Findings. If in fact the answer to experimental questions could always be predicted there would be little need for experimentation or analytic investigation. Not only is that not the case but often when a favorite hypothesis is contra indicated by data we improve our understanding of the phenomena far more than we would have had our hypothesis been confirmed. I will describe some findings which I feel support this viewpoint.

There are three pieces of research related to information requirements which are illustrative of the above. In one effort [4] an attempt to get a better handle on the information requirements of a division G-3 resulted in a comparison of survey data with SIMTOS data on the same division level scenario. It was found that the level of information detail identified as needed for mission accomplishment by those surveyed was not used by a similar group of SIMTOS players with the same mission. This of course suggested that people ask for more information than they need on the asumption that if it turns out to be relevant, it will be available, if not so what. Aside from implications for computer memory in automated systems, the assumption that "more" is better even if the "more" is relevant must be seriously questioned in light of findings in a 1962 study by Hayes [10]. There in the context of an air defense problem Hayes found that beyond some point the addition of more information though highly relevant tended to degrade performance. Finally a reduced detail map and a standard map were compared in terms of effectiveness for supporting both planning and combat requirements for SIMTOS. No significant performance differences were obtained though some users of the reduced detail map subjectively judged their maps, inadequate [6].

In another recent study [9] the utility of automating some of the analysis and production tasks associated with tactical order of battle processing was explored. In the comparison of automated and manual methods the accuracy and completeness of performance in the automated mode was better but there was no

difference in completion times. Since the participants were not instructed to emphasize one thing over another nor were they provided a time constraint one would expect automation to be faster. That finding led to the speculation that in the real world the most easily defined standard by which to judge the effectiveness of an analyst's work is time because the criteria of correctness are frequently lacking, and feedback for performance on that dimension is seldom provided. However failure to provide the product in a timely manner invariably results in a negative feedback. Thus the analyst is conditioned to behave in accordance with some system time function though there is no evidence that the time function should be the controlling variable to maximize overall effectiveness.

Incomplete data from a study which is still in progress and being conducted in a command and control test bed environment suggests that the better battalion command groups (as defined by having effective procedures for staff interaction and command and control) may perform less well in at least one type of operation - the covering force mission. The key problem seems to be excessive centralization of the decision process which results in an inability to make critical decisions within the narrow time window available for mission accomplishment. While there may be several alternative explanations to account for this behavior and it is too early to choose among them, one can't overlook the possibility that the criterion for "better command groups" may be erroneous.

As a final example another study which is currently on-going is comparing manual and computer aided performance in a movement analysis task. The computer aid is based on a moderately complex algorithm which computes shortest path/minimum time for as many as

10 units to 10 possible destinations taking into account type of unit, road conditions, weather, time of day etc. It is neither feasible nor necessarily desirable for all factors which might bear on route selection to be automatically taken into account. As an aid it is envisioned that a potential solution would be output which would be critically evaluated and modified by the user in light of special considerations which cannot be mirrored in computer software. Observations to date indicate that participants in the aided mode once having input the parameters of a given problem blindly accept the preferred solution without even visually inspecting the routes on a map. Yet in the manual mode a tentative solution once arrived at is subjected to a most careful scrutiny which frequently results in change. While there has been fear expressed that the introduction of computers would be resisted by those who feel the human decision making prerogatives are being relinquished to an inanimate beast that can't possible have the versatility, experience, creativity and other intangible assets that the human can bring to bear, these fears seem not to be reflected in any challenge or even review of the computer output. Thus the researcher and developer must be aware not only of those who have no trust in automation when they should but also those who trust unquestioningly when they should be skeptical.

If you have the impression that there is much more still unknown than known in regard to optimally melding human processing capabilities and limitations, information properties and parameters, and ADP hardware and software capabilities, you are probably correct. Efforts will continue toward resolving some of these questons but undoubtedly decision must be made regarding the characteristics to be required of interim battlefield information systems before all the answers are in. Indeed there is reason to believe that an ultimate system is not attainable in the foreseeable future and the acquisition and evolutionary enhancement of a succession of upward compatible interim systems in a viable approach assuming cost effectiveness for each iteration can be

demonstrated and there is concomitant research to insure the upgrading technology is available. There are risks associated with virtually all R&D efforts and in the absence of definitive performance data one must be particularly alert to overly optimistic technological promises and the ensuing predicaments which are best avoided.

5.0 Promises and Predicaments. Expected advances in computer systems based mainly on large scale integrated circuit technology could lead one to believe that the answers to most of our command and control problems is near at hand. Radical reductions in physical dimensions and power consumption concomitant with increased speed, memory capacity, ruggedness and reliability and at less cost are already being realized to some degree. Intelligent terminals should greatly facilitate man-computer interactions. It is predicted that by 1980 advanced intelligent terminals will accept 100 to 200 word speech input and have a voice response for a 2000 to 3000 word vocabulary. While the above bodes well in terms of exploitable potential there still is a long way to go in reducing the gap between the promise and reality of user performance within interactive computer systems.

It still seems appropriate, in spite of or perhaps because of the above, to continue focusing attention on aiding and complementing rather than replacing the human in future systems. Humans have limitations but so do computer systems. It may be enlightening to review some instances which tend to reinforce the notion that great care should be exercised before designing the human out of the loop.

It is virtually impossible to guarantee a large computer program to be free of error. Large systems consist of hundreds of thousands of instructions and while checkout and exercising will uncover most errors the occasional one that slips by can cause something of a sensation. For instance in 1971 a programming error caused a French weather satellite to unintentionally destroy 115 weather balloons it was trying to interrogate [1].

While this was not a catastrophic occurrence, in a slightly different context it could be. One need only to extrapolate from the reported time when an early version of the Ballistic Missile Early Warning System software allowed the rising moon to be mistaken for a missile raid [7]. That software to-day is both a big and costly problem can be gleaned from Figure [4]. If the probability of error increases proportionately or even monotonically with the amount of software code written then there is a basis for some trepidation in the size of those expenditures.

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Figure 4. The DOD Software Iceberg

A human operator may be able to compensate for system unreliability or malfunction. For instance in the Gemini VI mission, on board instruments indicated that lift off was initiated but sufficient thrust was not being generated to complete lift off. Wally Shirra sensed that lift off had not been initiated and therefore did not take emergency measures to eject. As a consequence what might have been an aborted mission was instead a success [5]. Man is inherently more flexible and adaptable to new and unusual situations than are automated systems. Typically automated systems are designed to cope with happenings which can be preplanned. However for information systems for the battlefield such plans may be the first casualty of war thereby probably

rendering these systems far less effective than had been anticipated. Essentially in the problem solving domain computers excel mainly on those problems that are well defined and quantitative. To a large extent the computer is dependent on man to provide the numbers - a task which man often does rather poorly. None the less, once generated, massaged in the computer and regurgitated in some aggregated form, all traces of their questionable ancestry are forgotten and an aura of respectability that many accept without question is radiated.

The need for advances in command and control capability is unquestioned. That these advances concern the ability to deal effectively, efficiently and rapidly with all dimensions of information seems self evident. That automation is necessary but not sufficient for satisfying this need is suggested. That efforts be continued to more fully understand both human and computer processes and characteristics requisite to defining the optimum synergistic relationship for meeting the command and control challenge is urged. And finally it is hoped that in future decades we will not look back on the present decade and again say [11] that no major military command information system has been developed within original cost and schedule estimates and still met its original performance objectives.

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COMMAND, CONTROL, COMMUNICATION AND TEAM DECISION THEORY

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Abstract. The coordination of decisions under uncertainty in a team leads to optimality conditions that are integral equations. A specific example of a two-division firm is developed to illustrate these conditions. Numerical imbedding techniques are used to solve the firm's decision problem. Extensions toward more general techniques and applications are indicated. These are clear implications for the problem of avoiding chaos under conditions of impaired communication between control centers.

1.0 Introduction. Organizations face decision problems that are more complex than the problems of a single agent. As Radner [17] points out, there may be differences among members of the organization with respect to possibilities of action, information, and preferences. In addition, there may be uncertainties about the actions of other members, making coordination difficult. The theory of team decisions ignores the possibility of internal differences in preferences in order to concentrate on the study of how communication helps coordinate the decisions of individual members.

In this paper, we look at the specific problem of computing optimal decision rules for a team with a given communication or information system. The optimal decision rules, it turns out, must satisfy a system of integral equations which can be quite complicated in general (non-linear, infinite limits of integration, with multiple variables of integration). Previous works in team theory have circumvented these difficulties by selecting problems with known solutions. Algorithms for the solution of the general problem have not yet been developed, but we have

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taken a first step in that direction by applying an imbedding technique to a specific numerical problem which does not have a closed-form solution.

Section 2 summarizes the decision problem of a multimember team. Section 3 looks at an economic application with the typical computationally complex team problem. Section 4 presents numerical results for this team decision problem. Major applications in command and control might be in avoiding chaos under conditions of degraded communication between sub-units. Section 5 sketches one such example. Conclusions and discussions are found in Section 6.

2.0 *Team Decision Theory*. A team is an organization whose members share a single, well-defined objective function. Such a harmonious group has but one problem: how are individual activities coordinated in an optimal fashion? Team decision theory explores such problems when the organization is uncertain about its environment and when information about the environment differs among team members. The decision problem reduces to the selection of rules of action that coordinate the interdependent activities of the teammates to maximize the expected payoff of the team.

Organizations are seldom harmonious and a game-theoretic model may seem more appropriate than a team-theoretic model. Since team theory is an element of a more general normative approach to the problem of "organization", Marschak and Radner [15] emphasized harmony in order to study the use of communication in the task of coordinating actions.[1] Team decision theory is an extension of Bayesian statistical decision theory to a multimember organization. The basic difference between these two decision theories is that the information provided each team member may be different. In statistical decision theory the action may consist of several components, but each component decision is based on the same information.

The team consists of n decision makers or teammates, indexed by i = 1, 2, ..., n. The basic elements of the team decision problem are as follows:

$\theta \in \Theta \subseteq R^{\ell}$: the unknown state of nature;

$A = (a_1,\ldots,a_n) \in \mathbf{A} \subseteq R^n$: the actions of the teammates;

$U(A,\theta)$: the team's utility function;

$Y = (y_1,y_2,\ldots,y_n) \in \mathrm{Y} \subseteq R^n$: the information of the teammates;[2]

$f(\theta)$: the team's prior probability density of θ;

$f(Y|\theta)$: the team's conditional prior probability density of Y given θ;

$\alpha(Y) = (\alpha_1(y_1),\ldots,\alpha_n(y_n)) \in \Delta$: the team decision function.[3]

The crucial points to notice are: (a) there is only one utility function, agreed upon by all members, (b) the utility function is not necessarily separable; that is, in general, $U_{a_i a_j} \neq 0$, (c) there is only one pair of probability densities, $f(\theta)$ and $f(Y|\theta)$, agreed upon by all members, (d) the information of the ith teammate, y_i, is different from the jth teammate's information, y_j, and (e) since the ith teammate knows only y_i, his action depends only on y_i; i.e.,

$$a_i = {}_i(y_i).$$

Each teammate wants to select decision rules that are coordinated to maximize the team's expected utility

$$W[\alpha] = \int_{\Theta}\int_{Y} U(\alpha(Y),\theta)f(Y|\theta)f(\theta)dYd\theta. \qquad (2.1)$$

How can we characterize the optimal decision rules for the teammates? Let $\alpha^*(Y)$ denote the optimal decision rule; that is

$$W[\alpha^*] \geq W[\alpha]$$

for all decision rules $\alpha \varepsilon \Delta$. Any arbitrary decision rule can be written as $\alpha_i*(y_i) + \delta_i\gamma_i(y_i)$ where δ_i is an arbitrary scalar and $\gamma_i(y_i)$ is a function of the ith teammate's information. Thus, any team decision rule can be expressed as

$$\alpha(Y) = \alpha*(Y) + D\gamma(Y)$$

where D is a diagonal matrix with elements $\delta_1, \delta_2, \ldots, \delta_n$ along the diagonal and $\gamma(Y) = (\gamma_1(y_1), \gamma_2(y_2), \ldots, \gamma_n(y_n)) \varepsilon \Delta$. The optimality of $\alpha*(Y)$ is represented by the marginal conditions

$$\left.\frac{\partial W[\alpha*+D\gamma]}{\partial\delta_i}\right|_{\delta_1=\ldots=\delta_n=0} = 0, \; i = 1,2,\ldots,n \tag{2.2}$$

for all $\gamma \varepsilon \Delta$. Radner [16] has shown that these conditions (2.2) can be expressed as follows:

Theorem (Person-by-Person Optimality): If $\alpha*(Y)$ is the optimal team decision rule then it must satisfy the following equations:

$$0 = \int_1 \ldots(i)\ldots\int_n \int_\Theta U_{a_i}(\alpha*(Y),\theta) f(Y(i),\theta|y_i)d\theta dY(i) \tag{2.3}$$

for all $y_i \varepsilon {}_i$. Here $f(Y(i),\theta|y_i) = f(y|\theta)f(\theta)/f_i(y_i)$ is the posterior probability of $Y(i) \equiv (y_i,\ldots,y_{i-1},y_{i+1},\ldots,y_n)$ given y_i.[4] The equations (2.3) can be written succinctly as

$$E\{U_{a_i}(\alpha*(Y),\theta)|y_i\} = 0 \text{ for all } y_i \varepsilon Y_i. \tag{2.4}$$

The optimality conditions are called "person-by-person" because they have the interpretation that the ith teammate, assuming his colleagues are using their best decision rules, picks a decision rule such that his posterior expected marginal utility equals zero no matter what information he might receive.

The optimality conditions for the single agent statistical decision problem are similar to (2.3) but not nearly so complicated. In statistical decision theory, the single decision maker has the privilege of waiting until the information is obtained, modifying his probability judgments using Bayes rule, and then selecting a single action to maximize posterior expected utility. The ith teammate cannot delay computation of his entire decision function because other teammates must know his decision rule in order to predict his actions and thus coordinate their decisions. The person-by-person optimality conditions must be solved simultaneously before the information is gathered.

The person-by-person optimality conditions (2.3) are, in the most general case, a non-linear interdependent system of integral equations. In some important special cases the solution is relatively easy. Most analytic contributions to team theory have concentrated on these specific solutions. However, for slightly different problems, the computation (on the back of an envelope or numerically) of $\alpha^*(Y)$ is non-trivial. The application of team theory to more realistic problems requires the development of algorithms for the solution of person-by-person optimality conditions.

3.0 *Multidivisional Firm: Quadratic-Uniform Example*. Suppose a firm consists of two autonomous divisions who produce different commodities in the amounts a_1 and a_2, respectively. The commodities are sold in a competitive market at prices P_1 and P_2. Because of random variations in supply and demand, the prices are not known precisely until the instant the commodities are sold. Each division separately gathers information about the market it sells in and uses this information to help select its quantity of output. Let y_i be the "price forecast" which the ith division uses in its decision making.[5]

The firm's total revenue is $P_1a_1 + P_2a_2$. Suppose that the total cost to the firm of producing quantities a_1 and a_2 is

$$C(a_1,a_2) = 1/2\ C_{11}a_1^2 + C_{12}a_2 + 1/2\ C_{22}a_2^2.$$

Notice that since C_{12} is non-zero, there is an interdependence between the production in two divisions.[6]

Assume that the firm believes that the relative prices of its two commodities are fixed but is uncertain about the price level. That is, the price vector that will be observed is $(\bar{P}_1\theta,\bar{P}_2\theta)$ where θ is a random variable and $\bar{P}_1$ and $\bar{P}_2$ are fixed numbers. The expected profit of the firm is

$$E\{\theta(\bar{P}_1\alpha_1(y_1) + \bar{P}_2\alpha_2(y_2)) - 1/2\ C_{11}\alpha_1(y_1)^2 - C_{12}\alpha_1(y_1)\alpha_2(y_2)$$
$$- 1/2\ C_{22}\alpha_2(y_2)^2\ .$$

Suppose that the price level, θ, and price forecasts of the individual divisions, y_1 and y_2, are uniformly distributed with the joint probability density

$$f(\theta,y_1,y_2) = \begin{cases} 3 & 0 \le y_1 \le \theta \le 1,\ 0 \le y_2 \le \theta \le 1 \\ 0 & \text{elsewhere.} \end{cases} \tag{3.1}$$

One can calcuate the needed posterior probability densities without much difficulty. They are given here in closed form.

$$f(\theta|y_i) = \begin{cases} \dfrac{2\theta}{1-y_i^2} & y_i \le \theta \le 1, \\ 0 & \text{elsewhere;} \end{cases} \tag{3.2}$$

$$f(y_j|y_i) = \begin{cases} \dfrac{2(1-\max[y_1,y_2])}{1-y_i^2} & 0 \le y_j \le 1, \\ 0 & \text{elsewhere.} \end{cases} \tag{3.3}$$

Using these posterior probability densities, the optimal decision rules $\alpha_1{*}(y_1)$ and $\alpha_2{*}(y_2)$ must satisfy the following system of linear Fredholm integral equations:

$$\alpha_1{*}(y_1) = \frac{\overline{P}_1}{C_{11}} \int_{y_1}^{1} \theta \, \frac{2\theta}{1-y_1^{\,2}} \, d\theta \; -$$

$$\frac{C_{12}}{C_{11}} \int_0^1 \alpha_2{*}(y_2) \, \frac{2(1-\max[y_1,y_2])}{1-y_1^{\,2}} \, dy_2 = \qquad (3.4)$$

$$2/3 \, \frac{\overline{P}_1}{C_{11}} \, \frac{1-y_1^{\,3}}{1-y_1^{\,2}} - \frac{C_{12}}{C_{11}} \int_0^1 \alpha_2{*}(y_2) \, \frac{2(1-\max[y_1,y_2])}{1-y_1^{\,2}} \, dy_2;$$

$$\alpha_2{*}(y_2) = \frac{\overline{P}_2}{C_{22}} \int_{y_2}^{1} \theta \, \frac{2\theta}{1-y_2^{\,2}} \, d\theta \; -$$

$$\frac{C_{12}}{C_{22}} \int_0^1 \alpha_1{*}(y_1) \, \frac{2(1-\max[y_1,y_2])}{1-y_2^{\,2}} \, dy_1 = \qquad (3.5)$$

$$2/3 \, \frac{\overline{P}_2}{C_{22}} \, \frac{1-y_2^{\,3}}{1-y_2^{\,2}} - \frac{C_{12}}{C_{11}} \int_0^1 \alpha_2{*}(y_1) \, \frac{2(1-\max[y_1,y_2])}{1-y_2^{\,2}} \, dy_1.$$

4.0 Numerical Solution. The integral equation (3.4) and (3.5) of the quadratic-uniform team example are of the following form

$$u(t) = g_1(t) + \int_0^1 K_1(y,t)v(y)dy \qquad 0 \le t \le 1,$$

$$v(t) = g_2(t) + \int_0^1 K_2(y,t)u(y)dy \qquad 0 \le t \le 1.$$

The forcing functions are identical except for multiplication by a scalar, $g_1(t) = k\, g_2(t)$. Similarly, the kernels differ only by multiplication by a constant, $K_1(y,t) = hK_2(y,t)$.[7] The kernels can be written in the following form

$$K_i(y,t) = \begin{cases} \beta_i(t) & 0 \le y \le t \\ \gamma_i(t)\ \delta_i(y) & t \le y \le 1. \end{cases}$$

That is, the kernels are semidegenerate. In the following we want to apply an imbedding technique for semidegenerate kernels to compute the solution of (3.4) and (3.5).

At this point in time our numerical algorithm can handle only a single integral equation. As a result the numerical problem was simplified by assuming that the multiplicative constants, k and h, were equal to one (or $C_{11} = C_{22}$ and $\overline{P}_1 = \overline{P}_2$). In this symmetric case, both integral equations are identical so it must be true that $u(t) = v(t)$ for $0 \le t \le 1$. Hence the problem reduces to the solution of the following single integral equation:

$$u(t) = g_1(t) + \int_0^1 K_1(y,t)u(y)dy. \tag{4.1}$$

By selecting $C_{11} = C_{12} = 1$ and $\overline{P}_1 = 1$ we can make this more specifically

$$u(y_1) = 2/3\ \frac{1-y_1^3}{1-y_1^2} - \int_0^1 \frac{2(1-\max[y_1,y_2])}{1-y_1^2}\ u(y_2)dy_2. \tag{4.2}$$

The numerical algorithm is based on the solution of a class of problems indexed by an upper limit of integration, x:

$$u(t,x) = g(t) + \int_0^x K(t,y)u(y,x)dy,\ 0 \le t \le x, \tag{4.3}$$

where the kernel K and the inhomogeneous term g are given, and the function u is to be determined for $0 \le t \le x$. The particular solution $u(t,1)$ provides the solution to the team problem.

A FORTRAN program for such a numerical solution is given in Kagiwada and Kalaba [10]. The numerical results of this program for the integral equation (4.2) are given in Table 1. As a

Table 1: NUMERICAL SOLUTION FOR OPTIMAL DECISION FUNCTION

Integration step size = 0.01

Y_i	$\alpha_i^*(y_i)$
0.0	0.3026
0.1	0.3081
0.2	0.3224
0.3	0.3434
0.4	0.3695
0.5	0.3996
0.6	0.4328
0.7	0.4685
0.8	0.5062
0.9	0.5455
1.0	0.5863

check on the results, it was shown that the solution points satisfied the trapezoidal approximation of the integral equation (4.2) with an accuracy of up to the fourth significant figure.

The numerical solution indicates that the optimal team decision rule for output is a monotonically increasing function of the price forecast. That is, when a division feels that the price level is going to be low then it should produce a relatively small quantity of its good; when the price level is forecast to be high, the division will produce large amounts of its good. Also, the numerical solution has a distinctly convex shape so that output is more sensitive to price forecasts when y_i is large then when it is small. When price forecasts are large a bigger gamble can be taken.

5.0 *Military Reconnaissance Teams*. Team decision theory is well designed to handle military problems of command, control and communication. The typical military decision problem involves several individuals who agree on an organizational objective; the environment of a military commander is often uncertain and hence actions are taken based on imperfect knowledge. Coordination of activities may be vital, yet communication may be severely limited. W. H. Hartman [8] motivated his investigation of team theory with the following military example.

A military reconnaissance team must locate certain features, such as a cave suitable for a supply depot or a path suitable for armored equipment in a mountainous or jungle terrain. The team is divided into several squads, which must search while avoiding detection by the enemy. Radio communication between squads must be minimized to prevent discovery and attack and hence the team must make decentralized decisions.

The team knows the rough local features of the territory via old surveys or satellite photographs but is uncertain about the detailed features of the terrain. Information is gathered to eliminate this uncertainty, but the team also must recognize that the quantity of information and time that is available will be

random. The squads are looking for the same type of object but the order in which they succeed and decisions they will make to secure the objective are unknown.

The reconnaissance problem requires some degree of coordination between autonomous decision makers. For given communication structures, optimal strategies should be provided for each squad. At a higher level, the communication structure should be selected to balance the payoffs of locating a suitable topographical feature and the costs of delays, communication and personnel. The theory of team decision making is an obvious tool to apply to such a command control and communication problem. Further research would have to include specifications of utility, probability distributions, communication structures and cost of information.

6.0 *Conclusions*. The development of techniques for specifying optimal decisions when there is uncertainty and information about the environment has had a major impact in many areas, from the management of corporations to the actions of military command. The application of this statistical decision theory was greatly facilitated by the development of conjugate probability functions, nonlinear optimization procedures, etc. Team decision theory promises to open new frontiers by investigating the multiperson decision problems involving communication and coordination. Team theory has existed as an analytic tool since the work of Marschak in the early 1950's (Marschak [13, 14]). Yet the number of applications of team theory is small (see Beckmann [4], McGuire [12], and Kriebel [11]). This, in part, is due to the difficulties of formulating and solving the basic team decision problem. Numerical techniques have not been applied to the team problem and hence most studies have been restricted to the examples which have well known closed-form solutions.

In this paper, we attempted to show how one step can be taken in the direction of generality; the optimality conditions of team decision theory were shown to be amenable to solution by

techniques of parametric imbedding. Many more such steps will have to be added before numerical solutions of more difficult team problems can be found routinely. We only need to point out that the solution procedure of Section 4 was dependent upon the quadratic assumption on utility functions, the compactness of the interval of integration, the symmetry assumptions that reduced a system of integral equations to a single integral equation, and the assumption of a scalar information variable.

One justification of numerical studies is that numerical solutions may lead to insights which can be translated into heuristic rules of thumb. We agree that the numerical approach to team decision theory will reinforce analytic conclusions with respect to optimal organizing and may even suggest regularities that should be investigated with analytic techniques. But more subtly, the authors feel that the numerical techniques may provide new analytic approaches to the study of team theory. In particular, the parametric imbedding solution technique may help us analyze the theoretical relationships between adjustment of parameters and change in decision rules.

Finally, "procedures" for selecting several decision rules to optimize a single objective function are the topics of investigation in the theory of decentralized optimization. The theory of decentralized optimization pioneered by Hurwicz, Arrow, Malinvaud, Dantzig and Wolfe, should provide further tools for investigating the solution of team problems.[8] The authors have begun some preliminary studies along this line, and hope to tie them into the numerical algorithm discussed in this paper.

FOOTNOTES

[1] The normative theory might be divided into three stages: (2.1) An organization must create a group objective function by constitutionally "aggregating" individual objectives (see Arrow [1], DeGroot [4], and Dalkey [5]).) (2.2) Individuals must be motivated to act with the group objective in mind (see Groves [7]), and

(2.2) Optimal strategies must be specified for individuals (this is the basic problem investigated in team decision theory).

2 The information that the ith teammate uses may come from two sources, a personal observation of the environment or a message from another teammate that summarizes his knowledge about the environment. Hence, it may seem more natural to make each component y_i a vector itself; but this will significantly complicate the results that follow (see Section 6 for further discussion). One might imagine that the vector of information has been reduced to a single "statistic".

3 The function space Δ is presumed to be some complete normed linear vector space. The only important distinction we want to make is that the ith component function, $\alpha_i(\cdot)$, depends only on y_i.

4 Radner [16] has also shown that differentiability and concavity of $U(A,\theta)$ in A for every θ makes (2.3) sufficient as well as necessary. We implicitly assume throughout that U is concave and differentiable.

5 There is no communication between divisions in this example. The comparison of expected payoffs with various communication structures can be found in Marschak and Radner [15].

6 The coefficients are assumed to satisfy the following restrictions $C_{11} > 0$, $C_{22} > 0$, $C_{11}C_{22} > C_{12}^2$ so that costs are convex in output.

7 $$h = \frac{\overline{P}_1}{C_{11}} \frac{C_{22}}{\overline{P}_2} \quad \text{and} \quad h = \frac{C_{22}}{C_{11}} .$$

8 See Arrow and Hess [3] or Heal [9].

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DESIRED FEATURES FOR MODELING COMMAND, CONTROL, AND INFORMATION

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The objective of this discussion is to set forth a statement of the desired features for means for analyzing command, control, and information processes in theater operations. Theater level is chosen so that the differences in the kinds of decisions at different levels of the hierarchy can be examined. The observation can also be made that different systems operate into the various elements of the command hierarchy. The need is to be able to assess changes in procedure as well as alterations in the systems. These procedural changes may be of greater significance than the available system changes.

The intention in this discussion is not to offer a solution or a description of a particular modeling approach but rather to suggest a concept for a structure so that analysis of command, control, and information systems can be accomplished. Certain assumptions are made in this discussion. First, communications can be modeled rather well. Second, sensor systems are readily represented. Third, combat interaction processes are generally amenable to existing techniques. In other words, the means for the analysis of physical processes are reasonably well in hand. The problem is the means by which command and decision processes can be analyzed. The available techniques for examining of these "social" processes in military operations leave much room for development.

While the purpose is methodology, a useful first step seems to be the identification of some of the desired qualities that a command, control, and information system should have. The model or analytic techniques used should provide the means to assess whether selected systems and procedure permit the commander to do these things. First, the commander and his staff should be able

to make estimates of opposing force capabilities and from these estimates anticipate situations that are likely to arise. From these anticipations and estimates the commander must be able to plan actions that use the force capability available to him. The success of the commander will also be affected by his ability to control the rate and intensity of combat according to his plans. The commander should be able to control movement and alert status of the forces. It should also be possible to examine how much better the forces function when the commander is provided with better or more timely information. In addition, the commander will want to manage supply and maintenance and protect those functions from destruction or disruption.

In the past, when evaluating new systems, the philosophy of the analyst and R&D manager has been that goals are achieved when information is provided and communications are available. When conducting analyses of campaigns a basic assumption is usually that the commander has perfect information. These conditions do not allow for either the vagaries of human performance or of the battlefield. This means that it would be desirable to be able to measure the capabilities of the command and information system to adapt to incomplete or erroneous information, surprise, and unexpected events. The commander should also be able to exploit opportunities or errors in decision no matter what their cause.

It is possible to imagine a number of measures of performance, including those that have been used in the past for communications systems. An example is error rate or delay. The final measure, however, of the effectiveness of any of these systems will be in terms of combat outcome, friendly force survivability, and the ability to modify and adapt plans to changing situations. In order to sample the complexity of the situations to be considered, a representation of a battlefield situation is shown in Figure 1. The illustration is presented to emphasize the time and space relationships. Distance from the FEBA is shown on the horizontal

axis, Red on one side, Blue on the other, and time on the vertical axis. In this illustration a regiment is represented as advancing on the right with armor leading. The armor stops to deploy in battalion formation for attack. Air defense units pass through and are deployed at appropriate locations. Artillery comes up from the end of the column, sets up and initiates preparatory fires. The armor units advance and are shown to be leap-frogging on the attack. On the Blue side a reconnaissance force with armor is at the most advanced position and at some point the advance of the attacker is detected. The deployment of the attacking units can be assumed to be following a definite sequence of events. Some events are precursors of others so that the appearance of the air defense units, for example, deploying in a certain way can be taken as indicators of coming armor or artillery actions. If the defending ground commander wishes to obtain air support, the US command system by which this done is represented in Figure 2. The interaction of the command system of the air forces and the ground forces is indicated. A request, for example, goes from the forward air controller to the Direct Air Support Center. Lower and higher levels of command are notified. Enroute sorties are diverted or aircraft are scrambled from airfields to attack the attacking ground force. These activities, of course, have to be coordinated with other air operations such as air defense and with the activities of the ground-to-air defense systems. These activities are incorporated into the fabric of command and control of all operations.

Figure 3 presents a simplified picture of the command structure from the threater commander through the ground component commander and the air component commander. As indicated in Figure 2, there is information transmitted up and down both of the air and ground force hierarchies and also from one hierarchy to another. Information sources provide input to the levels of command. An important feature to note is that there is a hierarchial distribution of information systems, that is, not all

sources provide information to all levels of command. The desired characteristics of the means to analyze these systems should include the ability to examine the effects of providing different kinds and amounts of information to the different levels of command. Representation of the kinds of actions taken at the different levels of command are indicated. For purposes of discussion, the command hierarchy can be further simplified to three levels: theater, intermediate, and engaged forces (Figure 4). With each level of command it seems reasonable to identify a number of functions that will be carried out. The level of detail, kinds of information, and resulting actions at each level may be different, but it is suggested that the basic functions at each level remain the same.

In a campaign there are a wide variety of events occurring on which information must be obtained. These events include the combat activities of both the friendly and the enemy forces, the status of forces, the needs for supply, maintenance, and other housekeeping chores. Certain sensors provide information on the events, these sensors range from the eyeball of the individuals on the scene to sophisticated electronic sensors (Figure 5). The array of interactions between the information collection means can be represeqted in a simple 2x2 matrix. Along the top are A forces and B forces and on the side A sensors and B sensors. The B commander obtains information from B sensors on both A and B forces, the B commander also obtains information from A sensors on A and B forces through captured reports and electronic intelligence means. The processes by which information is made available to a commander is most simply represented by identifiable steps of collection, processing, interpretation, and dissemination. It is important to emphasize that consideration is being given here to information on both friendly and enemy forces. At the beginning of this discussion one of the assumptions was that we know how to model sensor systems. The modeling, the processing and interpretation of data from specific sensors has also

been successfully accomplished in the past. Deficiencies arise, however, when the attempt is made to integrate the information collected by an array or package of sensors. For example, a reconnaissance aircraft may carry photographic equipment, IR, radar, ELINT sensors, and the eyeball of the pilot. When the aircraft flies over enemy territory each of these sensors collects different information over different widths of territory. When all of this information has been processed and interpreted it must be transformed so that the commander to whom it is presented is informed of the nature and character, location, and identity of units and weapons at a given time. The objective to be achieved from the information obtained from the reconnaissance aircraft and all other sensor systems is the construction of a situation map of the enemy forces. Since the information obtained will be incomplete, will have error, and will have been collected at different times, the information on that map will always be erroneous and incomplete. Similarly, the commander will have a map of the friendly forces based on the sensor systems by which those forces are observed. This map will also be erroneous and incomplete but with different time and place relationships. In a military operation the commander will examine these maps and endeavor to perceive the situation (Figure 6). If he is more cautious he may delay and request additional information. This will take time and mean that the orders that he gives will result in different actions and thus changes in effectiveness of those forces under his command when carrying out their combat functions. One of the problems then is to build an analytical approach for constructing a representation of these maps that is responsive to the integrated inputs of the variety of scenarios and reporting systems. Most likely there will be some probabilistic representation of the identity and location of units and weapons at a time. If it is possible to postulate that there is a reasonable number of situations that can be identified, then it might be possible to provide a current estimate of a situation as repre-

sented by the scenario inputs by comparison with a set of likely situations. The basis for the construction of reference sets of situations is that military units have recognizable formations and postures associated with different operations. It might be possible, for instance, to assign a probability distribution to the exercise of a situation. A further postulate is that there are a reasonable number of expected events that can occur at a given time in the future. Using a simple example, if a unit is moving along a road it may be presumed that after a lapse of a certain time, that the unit is probably located a certain distance down the road unless other actions interfere. It might thus be possible to construct an estimate of anticipated situations with a probabilistic description of the identity and location of units and weapons at a designated time in the future. The commander will wish to establish a number of tentative mission plans based on those current and anticipated situation maps and test those plans for possible gains and losses. Within a model of the decision processes a suggestion has been made that part of the planning activity of a commander could be represented by a simple and highly aggregate war game. The game would be played to establish alternative outcomes, gains, and losses. From these alternatives a model might use simplified linear programs or game theoretic techniques to assign different aircraft to tasks or to establish frag orders on the missions for the next day. This output of allotments or frag orders represents the actions of the commander.

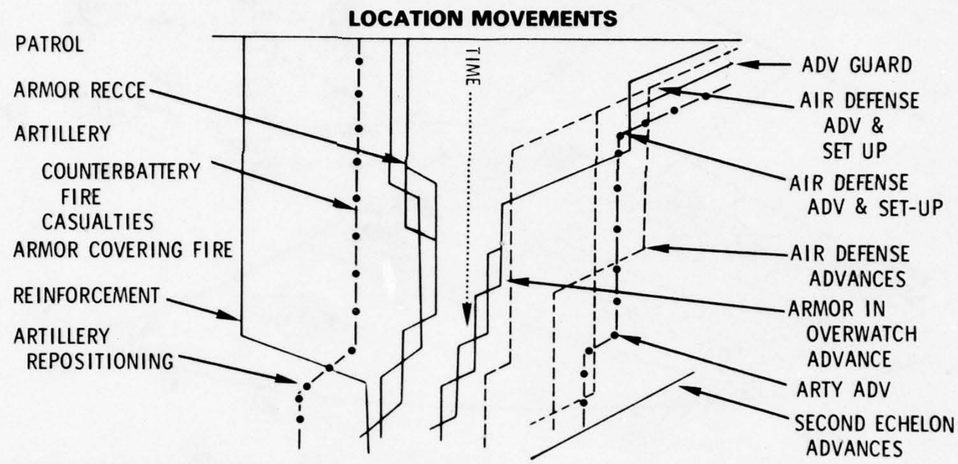
Within a model, the representations of the actions of the command system could appear as assignments, allocations, and movements as in a theater operation. The more difficult part to simulate is the modification of plans, particularly when situations have changed sufficiently that significant alteration in assignments and allocations should occur. For instance, if large forces have been allocated initially to the achievement of an objective and the results of the actions have been only partial achievement of the objective with great cost, how is it possible

to construct a simulation of a reasonable command such that new objectives are achieved? One possibility includes the use of threshold criteria within feedback loops.

The idea that the command process is a feedback system has arisen before. To be useful for the examination of the kinds of problems identified at the opening of this discussion, the feedback system would necessarily be hierarchical and the input and response characteristics at the different levels. Figure 7 shows a representation of such a system. In the upper corner is the input of the initial overall campaign plan and the basic policies and doctrine to be followed. In a model, the scenarios and objectives are input and initial orders are given to start the campaign. These orders are passed to lower levels of command, through the decision makers for implementation of the necessary actions. As a result of this, certain events occur. These include movements, attrition, supply demand, and need for repair. Information on these events is obtained, through sensors to the commands, more information may be requested, and the new situations perceived. The decision makers must adapt to the new situations and issue new orders to modify plans and institute new actions.

There are many elements of this concept of a model of a command-control-information system that are speculative and which will require some model formulations that are, at least, significantly different from things that have been done in the past. Alternative formulations and new ideas are needed. It would be desirable to institute a research program leading to the construction of an experimental model to test and evaluate such an analytic approach to the assessment of command-control-information systems. It appears that the problem of situation perception and transformation through decisionmaking is the most difficult part and the part on which the least work has been done. New perceptions and suggestions are earnestly sought.

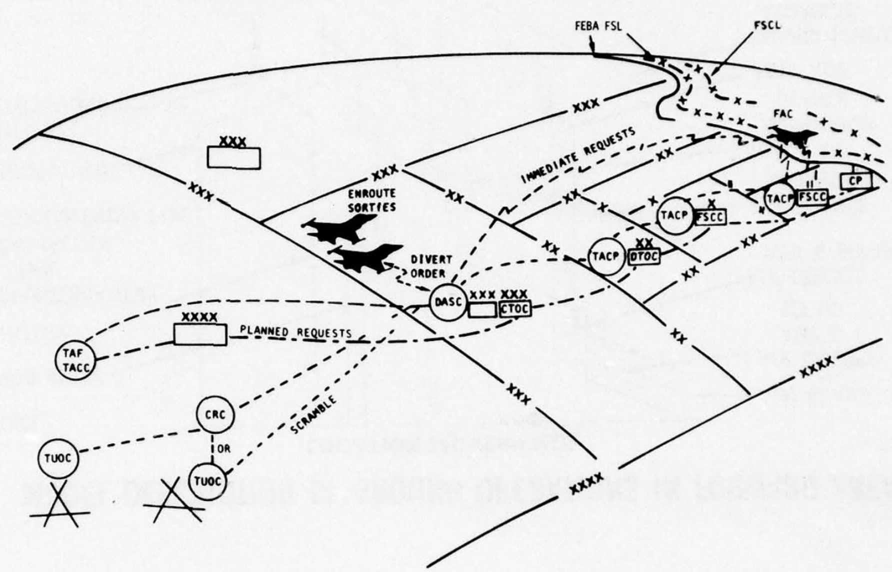
MODEL DESCRIPTION OF GROUND OPERATIONS IN FORWARD AREA

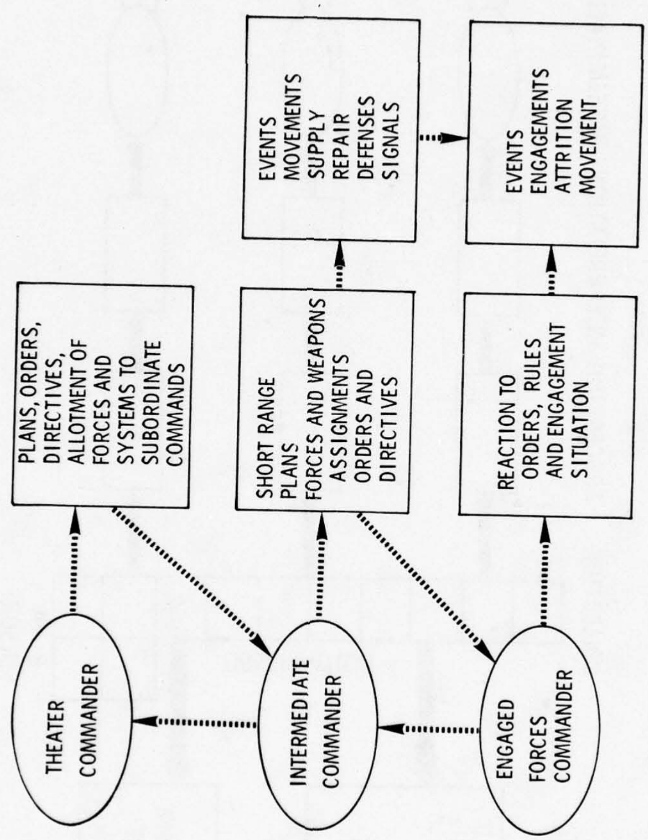


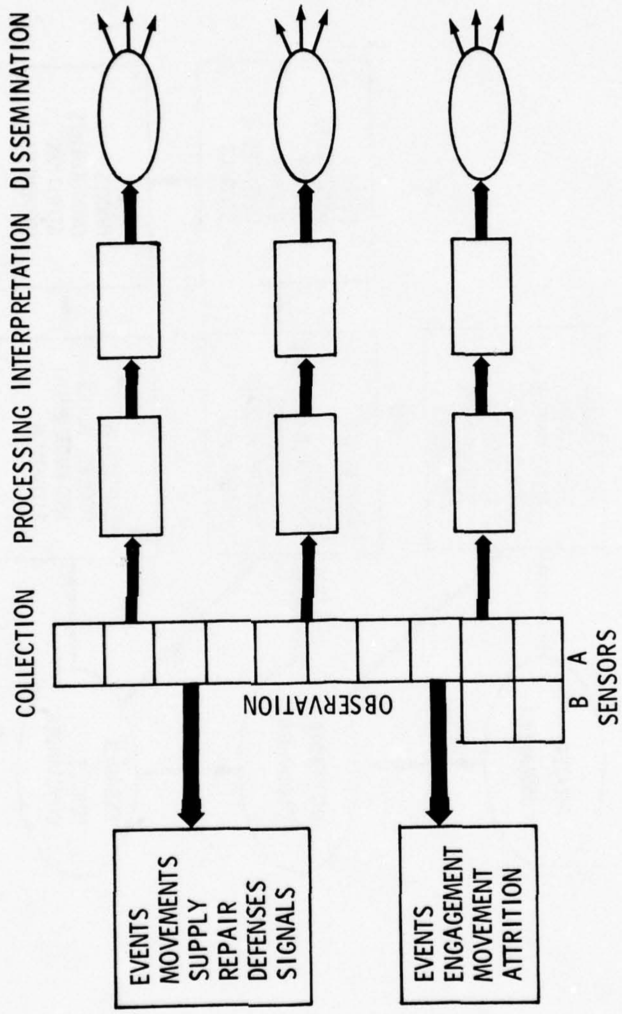
REPRESENTATIVE TIME-DISTANCE-EVENT SEQUENCE
MODEL MUST SIMULATE
MOVEMENT-SET/UP-MESSAGES-FIRES-
TARGET ACQUISITION-CASUALTIES-RESUPPLY
CLOSE AIR SUPPORT-BATTLEFIELD INTERDICTION

ARMOR
AIR DEFENSE
ARTILLERY

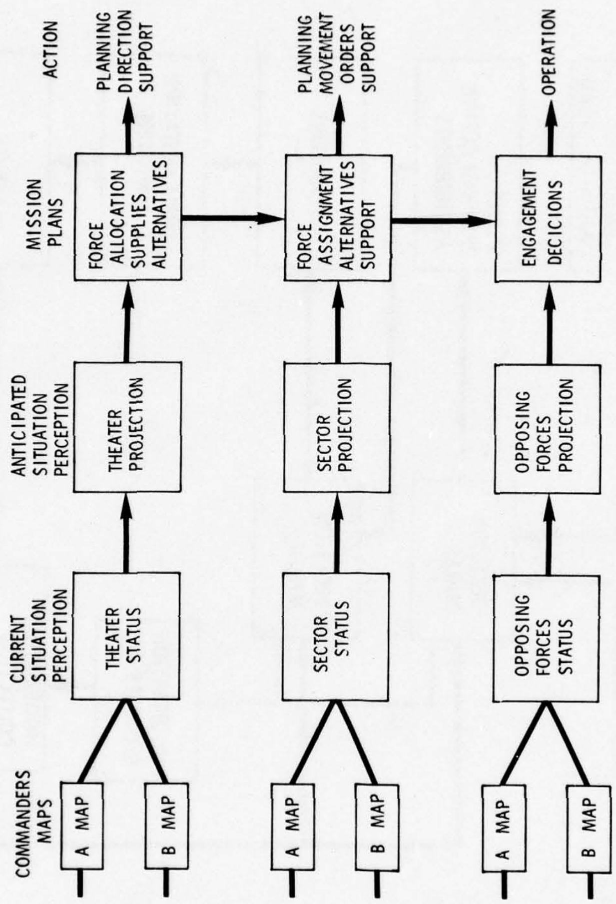
OFFENSIVE AIR SUPPORT COORDINATION

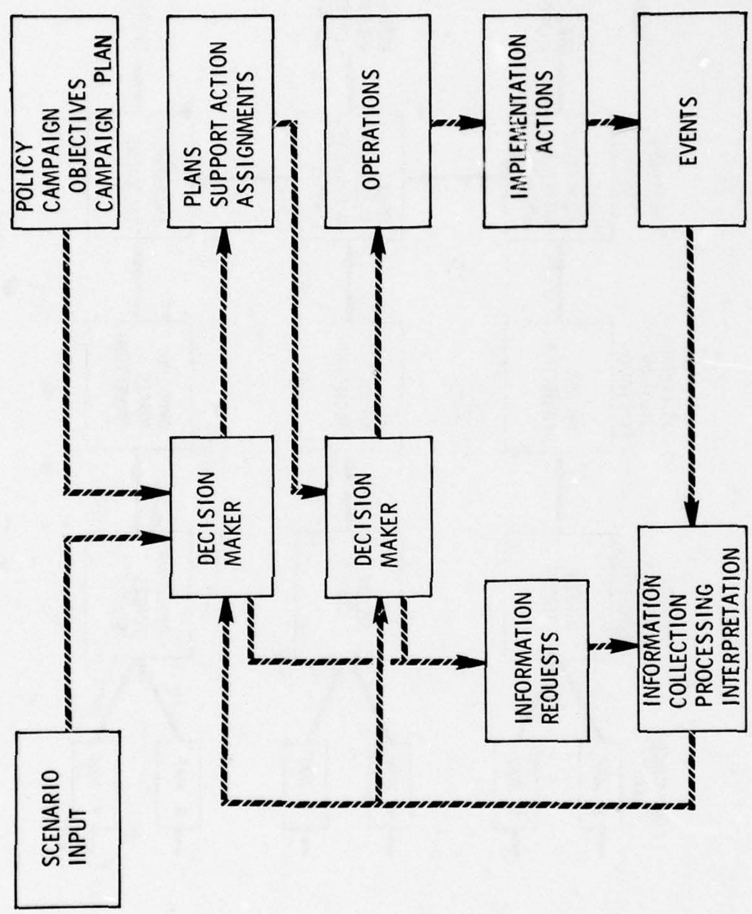



THEATER COMMANDER
INTERMEDIATE COMMANDER
ENGAGED FORCES COMMANDER
PLANS, ORDERS, DIRECTIVES, ALLOTMENT OF FORCES AND SYSTEMS TO SUBORDINATE COMMANDS
SHORT RANGE PLANS FORCES AND WEAPONS ASSIGNMENTS ORDERS AND DIRECTIVES
REACTION TO ORDERS, RULES AND ENGAGEMENT SITUATION
EVENTS MOVEMENTS SUPPLY REPAIR DEFENSES SIGNALS
EVENTS ENGAGEMENTS ATTRITION MOVEMENT



COLLECTION
PROCESSING
INTERPRETATION
DISSEMINATION
OBSERVATION
A
B
SENSORS
EVENTS
MOVEMENTS
SUPPLY
REPAIR
DEFENSES
SIGNALS
EVENTS
ENGAGEMENT
MOVEMENT
ATTRITION


COMMANDERS MAPS
CURRENT SITUATION PERCEPTION
ANTICIPATED SITUATION PERCEPTION
MISSION PLANS
ACTION
A MAP
B MAP
THEATER STATUS
THEATER PROJECTION
FORCE ALLOCATION SUPPLIES ALTERNATIVES
PLANNING DIRECTION SUPPORT
A MAP
B MAP
SECTOR STATUS
SECTOR PROJECTION
FORCE ASSIGNMENT ALTERNATIVES SUPPORT
PLANNING MOVEMENT ORDERS SUPPORT
A MAP
B MAP
OPPOSING FORCES STATUS
OPPOSING FORCES PROJECTION
ENGAGEMENT DECICIONS
OPERATION


SCENARIO INPUT
POLICY CAMPAIGN OBJECTIVES CAMPAIGN PLAN
DECISION MAKER
PLANS SUPPORT ACTION ASSIGNMENTS
DECISION MAKER
OPERATIONS
INFORMATION REQUESTS
IMPLEMENTATION ACTIONS
EVENTS
INFORMATION COLLECTION PROCESSING INTERPRETATION

THEATER COMMANDER

INFORMATION SOURCES	GROUND COMPONENT	AIR COMPONENT	ACTIONS
SIGINT SATELLITE AWACS	ARMY COMMANDER	AIR FORCE COMMANDER TACTICAL AIR FORCE (TAF) TACTICAL AIR CON-TROL CNTR (TACC) AWACS CONTROL & REPORTING CNTR (CRC)	LONG RANGE PLANS, ALLOCATION OF AIR AND GROUND RESOURCES
RECCE FLIGHTS RPVS UNATTENDED GROUND SENSORS	CORPS CORPS TACTICAL OPN CNTR (CTOC)	DIRECT AIR SUPPORT CNTR (DASC)	PLANS, UNIT REPLACE-MENT, RESERVE AND SUPPLY ALLOCATION. ATTACK, DEFEND ALLOT FORCES
FORWARD AIR CONTROLLER (FAC) FORWARD OBSERVER (FO) AIRCREW DEBRIEFINGS	DIVISION DIV TACTICAL OPN CNTR (DTOC)	TACTICAL AIR CONTROL PARTY (TACP) AIR LIASON OFFICER (ALO)	GENERAL SUPPORT, RESUPPLY, SHORT RANGE PLANS, ATTACK, DEFEND, DELAY, COORDINATES ATTACKS
SCREENING FORCES RECCE PATROLS	BRIGADE FIRE SUPPORT CONTROL CNTR (FSCC)	TACP ALO	PLANS, ATTACK, DEFEND, DELAY
REPORTS	BATTALION (FSCC)	TACP FAC	ENGAGE, DISENGAGE DIRECTS ATTACKS

DECISION SUPPORT IN A BATTLEFIELD ENVIRONMENT

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The objective of this paper is to give an overview of some work we have done on decision aiding under support from the Army Research Institute. This work was reported in three technical reports (Levit, Alden, Erickson and Heaton, 1974). It is also an extension and application of prior work we had done on decision styles (Henke, Alden and Levit, 1972). Although a difficult concept to work with, individual differences in decision making and information is a recurring theme in the literature of both decision making and command and control.

During this period an extensive literature review was conducted of decision-making, cognitive styles, decision-aiding, and man-computer interaction. This review was greatly benefited by a concurrent project of setting up a dedicated computer facility to provide us the capability for two-person interactive gaming. Initially we called the facility the Man-Computer Laboratory; recently we changed the name to Command and Control Simulation Facility to reflect current trends and projects.

The term "battlefield environment" in the title is perhaps a little misleading. We have been working with the Army's Division Tactical Operations Center (DTOC). The DTOC is not at or near the front line where troops and weapons are in line-of-sight contact; it is typical 15-20 kms behind the FEBA (forward edge of the battle area) where it is not immediately involved in the melee of armed conflict. The functions of the DTOC are to acquire and integrate information on hostile and friendly force movement in the divisional area, make plans for deployment of divisional resources, and monitor the execution of these plans. It is a decision situation with a heavy flow of information, periods of rapid change, and a requirement for rapid, real-time update and

response. This situation is markedly different for one of national crisis where events tend to move more slowly and there is more time for analysis and evaluation.

The topics to be covered in this paper are the following:

- Related aspects of future tactical decision situations
- Need for decision aiding
- Criteria for decision aids
- Decision support system
- Decision styles and adaptive aiding
- Application to SIMTOS

In addition, some conclusions are presented about the state-of-the-art and methodology in decision aiding and decision styles.

Related Aspect of Future Tactical Decision Situations The complexity, speed, range and fire power of modern weapon systems have had a significant impact on the flow of events and the complexity of tactical decision making. Future tactical conditions can be characterized as:

- More rapid speed of engagement. The speeds with which modern military vehicles can close on each other in approaching the limits of human response time.
- Longer range of detection. The sensitivity and differentiation of sensors systems has provided a capability to detect enemy action at greatly increased ranges. The number of things that can be detected has also increased.
- Longer range of engagement. Events can take place at ranges far exceeding those at which direct sensory confirmation can be obtained. Information about events is obtained in symbolic, transformed or encoded form. It is thus necessary to act within highly abstract representations of the tactical situation.
- Increased weaponry. The diversity, range, speed and power of weapons have increased to provide a multi-threat environment and multi-threat response capability.

- Increased complexity of systems. The diversity of systems; multiplicity of sensors, information sources, and displays; the use of advanced electronics and data processing; and increasing levels of automation all combines to provide a complexity that is difficult to conceptualize, comprehend and manage.
- Reduced manning. There is increasing pressure to reduce manning, not because we know how to eliminate man from systems but because personnel costs are accounting for increasing portion of costs in relatively stable budgets. This trend has tended to work in opposition to the increased complexity of systems.

The conditions lead to the following requirements for decision making in future systems.

- Decisions process must be completed within seconds.
- Initial time critical steps preprogrammed. The rates of closure of modern weapons are so rapid that early detection and evaluation are critical. Man's variability in such tasks cannot be tolerated. Therefore, some *preprogramming and automation are necessary.*
- Man must process in parallel to the system rather than in series with it. He must be able to follow what the system is doing and assess the impact and feasibility of the course of actions.
- Man's role limited to final step. Man's function will be primarily one of selection or evaluation of action alternatives.
- Man has override responsibility. Command will be exercised by exception and interceding to override the course of events that the commander judges to be undesirable.

Need for Decision Aids These considerations in turn define data requirements to support the command and control process in future systems. First, timing is critical. Information must be provided

in a timely manner in a continuing, dynamic, rapidly changing situation. Second, only data relevant to a decision must be presented. Finally, data must be immediately interpretable. The command staff does not have time to do any transformation or interpretation of the information presented to it.

The process of decision making, especially as it applies to tactical decision making, should be defined to facilitate further discussion. Tactical decision making consists of a sequence of functions and typically it is defined by differentiating these functions. Several different definitions are in the literature; they differentiate the process in slightly different ways.

The definition presented here divides the process into five major functions, as follows:

- Information collection
  - sorting
  - structuring
- Problem analysis
  - discover relationship
  - analyze risks
  - generation options
  - evaluate options
- Selection of action alternative
- Implementation of decision
- Monitor progress
  - monitor feedback on events
  - recognize changes
  - modify decision
  - override

Although there is a logical temporal sequence, the functions are in fact iterative and overlapping.

The need for decision aiding can be identified from the following generalizations about decision behavior, taken from Schrenk (1969).

- Individual differences are large. The variance of measures of decision behavior is typically large. There are better and worse decision makers. Selection is one way to reduce this variance. Another way is to provide aiding techniques that are adaptive to these individual differences. It is postulated that the variance reflects differences in decision, or cognitive, style.
- Use of information
  - excessive information is often sought
  - use of multi-dimensional information is limited
  - early information is given excessive weight
- Selection of action alternatives
  - too few alternatives are considered
  - commitment may be delayed too long
  - change in erroneous commitment is slow

In spite of all these shortcomings, the decisions made are generally appropriate.

Criteria for Decision Aids A set of desired characteristics of decision aids were identified to guide the development of aids. These characteristics can also serve as criteria against which an aid can be evaluated. The criteria are presented here under three headings: performance, workload reduction and relational criteria.

These sets of criteria are as follows:

Performance Criteria

- Improves decision quality by reducing error, decreasing decision time
- Generates, classifies and weights response alternatives
- Provides rapid feedback on decision consequences
- Helps in the formulation and application of rules
- Encourages seeking new relationships by assisting database restructuring
- Anticipates and helps prepare for contingencies
- Aids in accepting discrepancies between expectations and

the real world

Workload Reduction Criteria

- Assist user to discriminate relevant from irrelevant information
- Allocate functions between man and computer
- Assist parallel information processing
- Aid in keeping track of parallel events

Relational Criteria

- Requires a minimum of training to use
- Is simple to implement and reliable in operation
- Generates confidence and trust in the user
- Encourages interaction with automated system
- Facilitates communication among the command team
- Responds to user variability

Decision Support System A review of the literature on decision aiding and an analysis of tactical decision tasks led to the concept of a Decision Support System (DSS). The central idea in the DSS is to provide support to the entire decision process in a given situation. An integrated complex of decision aids is provided with each component aid designed to satisfy an identified requirement. A mixture of aiding methods is used. The DSS is treated as an interactive man-computer unit.

An important element of the concept is that the aids within a DSS will support, or aid, human information processing. There are points in the decision-making process where human capability is inadequate because of limitations, variability or tendencies to make errors. The aid would provide support at these points. The alternative to this approach is to design the aid or decision support system to solve the decision problem and supplant man or put man in a position of supporting the decision system. This latter approach is rejected. Man has the primary position.

Three classes of aids were identified for inclusion in a decision support system:

- Estimate of situation - Information to structure and interpret the tactical problem
- Resource allocation - Information and communication for systematic and optimal allocation of resources
- Contingency planning - Assess consequences of alternative actions; play "what if"

Decision Styles and Adaptive Aiding The idea of the decision style is basis of our approach to making aids adaptive to individual differences. The terms decision style and cognitive style will be used somewhat interchangeably.

The relevant literature is voluminous and heterogeneous. Particular investigators, or groups of investigators, have pursued studies relevant to a single dimension of style but there has been little integration of these dimensions into global concept of cognitive style.

Intensive examination of the literature, however, revealed that most of the studies could be grouped under three categories: abstract-concrete; logical-intuitive, and active-passive. These categories were adopted as independent dimensions of cognitive style. The selection of these dimensions was done by a process of "verbal-conceptual eyeballing" of the literature rather than empirical methods such as cluster or factor analysis. Direct empirical support is desirable but it was not attainable with the resources available. The present model is presented as a first approximation which was formulated as an aid in structuring the design of decision aids.

Each style dimension is associated with a dimension of information and an aspect of decision making, as follows:

Style Dimension	Dimension of Information Processing	Aspect of Decision Making
Abstract-Contrete	Type of Information used	Information Acquisition
Logical-Intuitive	Form of information processing	Information Assimilation
Active-Passive	Activity level in information acquisition-processing	Action selection

Each style was also hypothesized to have a form or format of information presentation associated with it.

Style Type	Information Presentation Correlate
Abstract	Symbolic
Concrete	Liguistic
Logical	Structured Data
Intuitive	Global Associative Data
Active	Partial Data Array
Passive	Complete Data Array

Each dimension of decision style was differentiated into behavioral correlates. They were based on common findings in the research literature. Much of the terminology has standardized meaning in the psychological literature which does not always correspond to the everyday usage. These behavioral correlates are summarized below for each dimension.

Abstract Traits	Concrete Traits
1. Field independence	1. Field dependence
2. Objective	2. Subjective
3. Control over impulses	3. Less control over impulses
4. Symbolic	4. Linguistic
5. Visualizer (non-manipulative)	5. Non-visualizer (manipulative)
6. Tolerance for ambiguity	6. No tolerance for ambiguity
7. Ability to change set	7. Less ability to change set
8. Open mind	8. Closed mind

Logical Traits	Intuitive Traits
1. High information demand	1. Low information demand
2. Caution	2. Confidence
3. Seeks order and regularity	3. Less order and regularity
4. High need achievement	4. Low need achievement
5. High fear of failure	5. Low fear of failure
6. High anxiety	6. Low anxiety
7. Analyzer	7. Synthesizer
8. Sharpener	8. Leveler
9. Narrow categorizer	9. Broad categorizer
	10. Global

Active Traits	Passive Traits
1. Mental alertness	1. Mental slowness
2. Seeks to increase activity level	2. Seeks to reduce activity level
3. High need for novelty	3. Prefers status quo
4. Seeks uncertainty	4. Desires certainty
5. Manipulative	5. Seeks internal stimulation
6. Seeks external stimulation	6. Seeks intensity
7. Seeks meaningfulness	7. Needs organization
8. Needs less organization	8. Tendency to introvert
9. Tendencies to extrovert	9. Long attention span
10. Short attention span	

Each of the three style dimensions was treated as a dichotomy and this decision yielded eight different decision types into which people can be classified. Each decision type was assumed to have characteristic errors or aberrations of information processing; a good decision aid would compensate for or buffer these errors and abberrations. Similarly, the individuals in a given type will have preferred ways of operating which the aid should accommodate.

A paper and pencil measuring device was developed to give a score on each of the eight "poles" of decision style. The device is called the Decision Styles Measuring Instrument (DSMI). It consists of several situational scenarios about which the respondent must choose as he would proceed in the situation. The DSMI was designed for administration in one hour for ease of incorporation in experimental procedures. Further details on the DSMI may be found in (Levit, Alden, Erickson and Heaton, 1974, Vol. 2).

Representative tactical decision profiles were developed for each of the eight types. The profile for active, abstract, logical is summarized below as an illustration.

1. Functions best with a broad range of information
2. Information should have inherent structure, easily defined and constant
3. Requires concise, accurate display of information which will confirm his concept of the sutuation
4. Level of detail need not be great
5. Plans problem around his concept of situation
6. Will query data base selectivity to assess adequacy of his plan
7. Will not need overall review of situation; will depend on his experience in similar situations
8. Crucial to give him information that might cause him to change his expectancies
9. Data in disagreement with his approach must be emphasized
10. Must be encouraged to constantly re-evaluate his plan

Note that items 1-6 are descriptive of a mode of operation and preferences; items 7-10 deal with shortcomings which must be counter-acted.

The tactical decision profile for active, concrete, intuitive is much briefier.

- Will sample the data base in great depth, across a broad range of topics.

- Will benefit from any device that would help him correlate data across categories of information
- Tends toward rigidity after he has developed his approach to the situation
- Will change his approach if presented with the appropriate facts

Application to SIMTOS The objective of this study was to evaluate adaptive decision aids that had been designed and incorporated into the SIMTOS. SIMTOS is a simulated tactical operation system at the Army Research Institute. The scenario used was set in a European environment and consisted of a defense of the Hof Gap area. Both planning and combat phases were included. The aids were designed to support the Division Operations Officer (G3).

The study turned out to be more exploratory than hypothesis testing. It was intended to be a rigorous experimental evaluation. However, the complexity of the problems of incorporating the aids into the SIMTOS scenario precluded achieving that objective within the available time.

Two aids were designed: estimate of the situation and resource allocation. The situational estimate aid consisted of an automatic tracking and updating of elements of information designated by the G-3. The designated elements are called Standard Requests for Information (SRI). Each SRI is automatically updated and displayed to the G3. The SRI is an aid to recognizing or attending to changes in key elements in the combat situation. A maximum of 30 SRIs were available. The resource allocation aid consisted of a display of all friendly units within range of a designated target and the available fire power.

Two groups were run; they differed in the decision aiding provided, as follows:

Aided Group

- Planning phase
  - Estimate of situation

- Combat phase aids
    - Estimate of situation
    - Resource allocation

Unaided Group

- Combat phase aid
    - Resource allocation

The resource allocation aid was provided to both groups in order to reduce the complexity of the experimental task. Fire support is not a part of the G3 role and he does not have the facilities to perform that task. There were ten participants in the study ranging in rank from Major to Colonel. Nine, one-hour sessions were run.

Several performance measures were collected. They are summarized below in two categories of Information Processing and Tactical measures.

	Planning	Combat
Information Processing		
1. Sources sought	X	X
2. Action ratio	X	X
3. Error ratio	X	X
4. Redundancy ratio	X	X
5. Information acquisition ratio	X	X
6. Resource allocation usage efficency		X
7. Firing time		X
Tactical		
1. Defensive plans	X	X
2. Friendly force attrition		X
3. Enemy force attrition		X
4. Distance surrendered		X
5. Friendly force weapon expenditure		X
6. Events		X
7. Enemy force objectives reached		X

The results are extensive and only a representative sample will be presented here. Inferential statistical analysis was limited due to the small number of subjects. Performance of the aided and unaided groups on distance surrendered weapon expenditure and friendly force attrition is presented in Figures 1, 2, and 3. The performance of the aided group was slightly superior.

Conclusions In general, the concepts of adaptive decision aiding and the decision support system have been formualted and there is weak support for the usefulness of aiding, the concept of a decision support system and aiding adaptive to decision style. The model of decision styles has been formulated to the point where it can be stated more rigorously and hypotheses can be generated and tested.

There are also several significant problems that can be identified. First, at the current state of the art, aiding is application specific; it is difficult to formulate general principles. Second, data base structure is critical to useful aiding. The accessability and manipulability of the data is important to decision aiding and they are dependent on the data base structure. Third, the research and development process is very time consuming. Large quantities of data are collected at great expense but with a decreasing yield of information per cost. Finally, current research methodology and tasks in decision-making are too simple to provide anything substantial in generalizations to tactical decision-making. In addition, the absence of models of the tactical decision process make it difficult to apply research findings to this context.

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PROCEEDINGS OF THE WORKSHOP ON DECISION INFORMATION FOR TACTICA--ETC(U)

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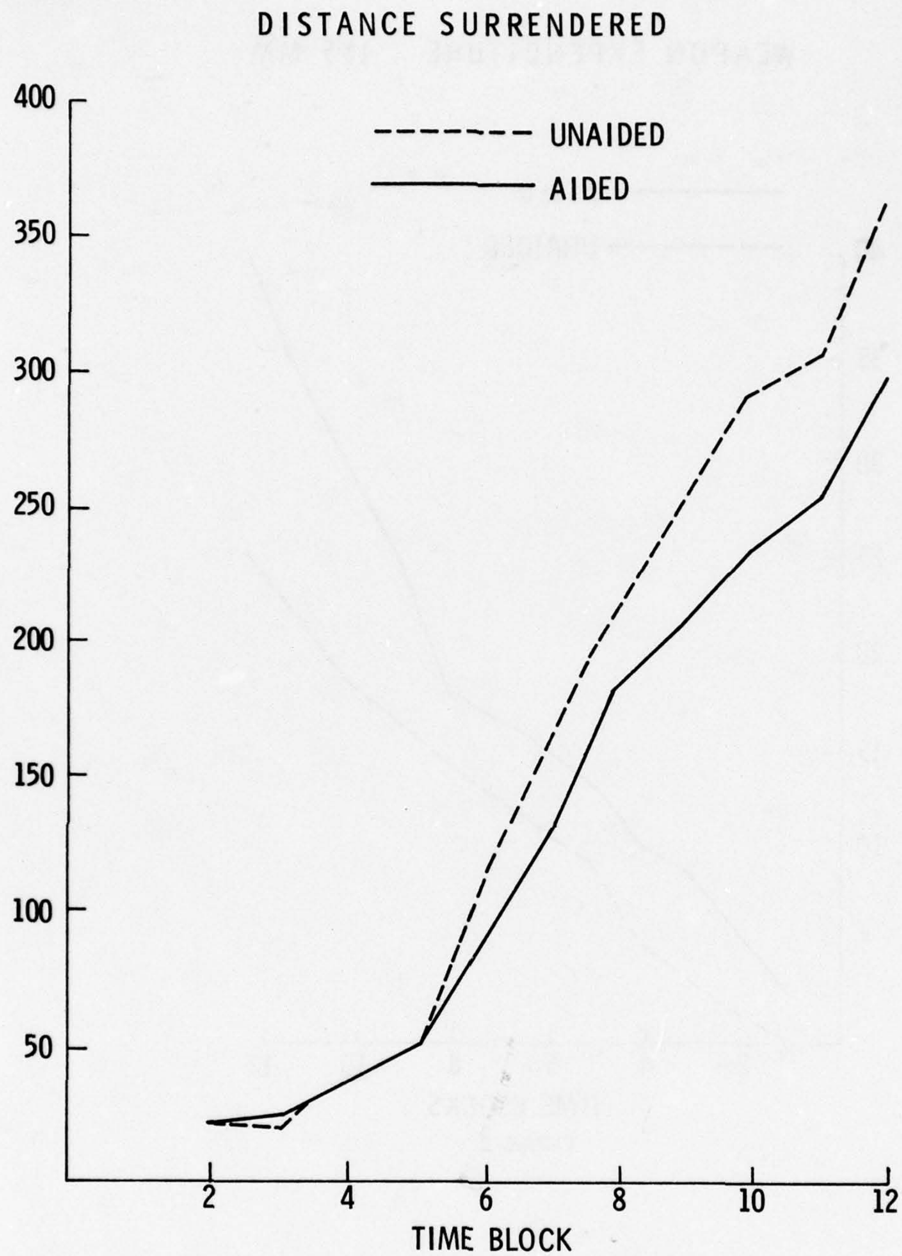
DISTANCE SURRENDERED
400
350
300
250
200
150
100
50
UNAIDED
AIDED
2
4
6
8
10
12
TIME BLOCK

FIGURE 1

WEAPON EXPENDITURE : 155 MM

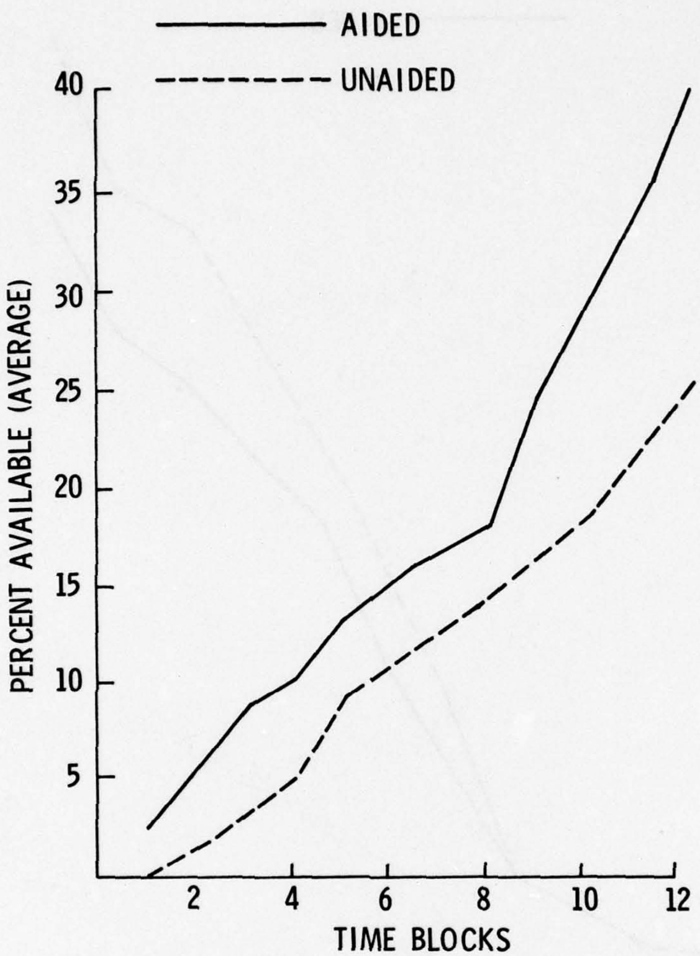

FIGURE 2

FRIENDLY FORCE ATTRITION

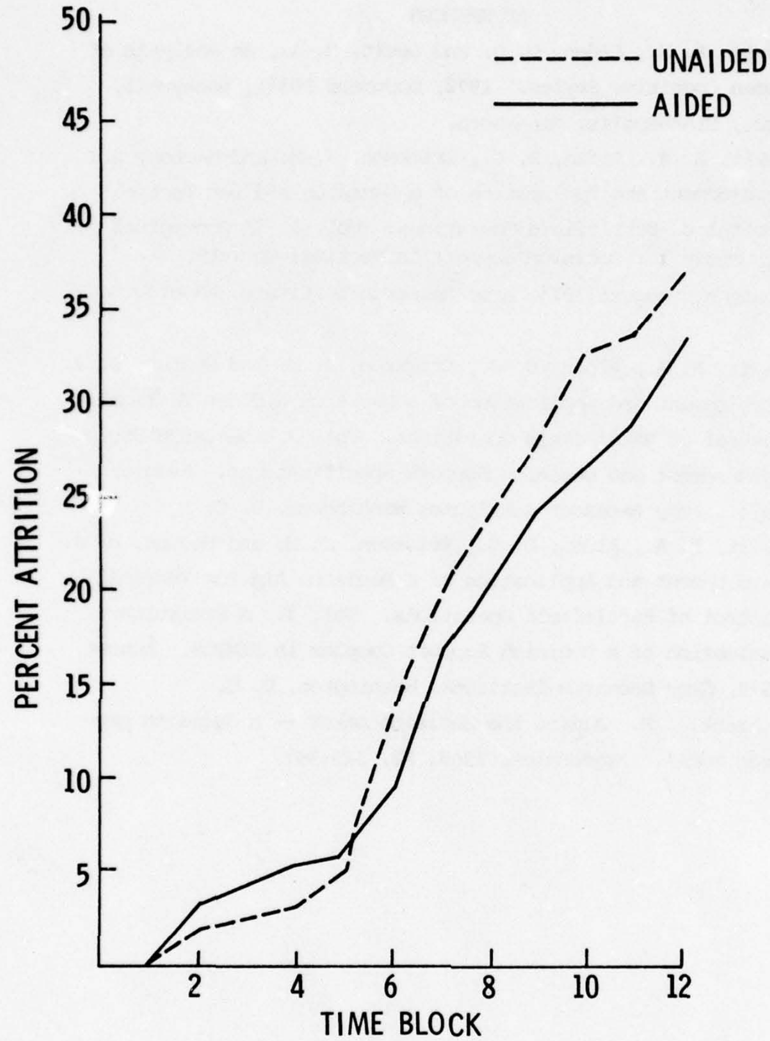

FIGURE 3

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DISCUSSION

Dockery: I would like to ask Dr. Modrick a question. It appears that what you are saying is that Command and Control is not picking up a mike and saying the mike is dead. Rather they are trying to push something psychic through a wire and get it back. In your test I would like to know - did you end up with some profile? In other words, has the Military System empirically made some match between our communication system and the kinds of officers they selected at various levels? In other words, did they come up with some sharp profile that was repeated more often than not? There are eight combinations - did one appear more often than the others?

Modrick: I am reluctant to respond to that question because I am going on memory. I think on this level the dominant profile was active abstract intuitive. My memory was incomplete. Thirty percent were active/abstract/intuitive and forty percent were passive/abstract/logical. Looking at each dimension, they were split evenly on active-passive and logical-intuitive but 90% were abstract rather than concrete. I would have to do some thinking now to say what that profile represents. They were an impressive bunch of people, incidentally. Recently we had the opportunity to administer this to six Captains, which is a very small sample. The Captains have very different profiles. They had a characteristic profile, but it was different from the Major or Colonel type. I don't recall off hand what this designated, but I do recall that it was different. There was one officer, a Captain, who had a profile like the Major and Colonel. He seemed to be in a lot of ways the sharpest. There was something about him that was different, there is no question about that. I got to know these men before we gave them the test.

Orlansky: Assuming that this structure of eight different types is true and assuming that generally you find it out about people and assuming that it is not situationally dependent. What would any of this have to do with the design of a Command and Control system?

Modrick: The assumptions are perfectly acceptable. The things are stable, I have no doubt about that. What does it mean to a command and control system: It means a lot of things. It says a great deal about how you put together an information system. For one thing, it is dependent on who the user of the information is. I think this is a good bit of common sense as a matter of fact. One of the stories I have heard repeatedly concerns what happens when there is a change in command? A new man comes in and you certainly will notice within a year there is a very big change in personnel in the Command Headquarters. The staff changes. I think he picks the man who fits his style. I think every time the Command changes there is one man who doesn't fit the Commander's style and there is a conflict between them and that man goes. There is usually some ill feelings. But within a year the new Commander has got things organized the way he likes to work. This is also what I think is Command perogative on the part of the Commander. I have heard Commanders say, "By God, as long as I am Commander you are going to do things my way."

There has been one demonstration that I know of where this makes a difference. Gordon Pask in England has worked on what he calls "learning styles". *He has identified two kinds of learning* styles. It is very difficult to show substantial differences in decision aiding. What Gordon Pask does, he sets up a person with the *wrong* type of style. He takes a Type "B" individual and programs Type "A" for him and vice versa. Those guys just have one hell of a time. I think it has a great deal to say about software, how you organize the data base, what kind of display you use.

Major Franklin: Let me submit something to you. It is more of a statement to hit the impact heavily. We are currently in the process where we select commanders by a Command Selection Board. There is a sterotype typical of the officer that fits what that board feels to be the appropriate career pattern for Command Selection. I am going to put out to you as an operator that you

have a given and it is a personality make-up that you want design to. I think sir, that you will identify this. I think you have seen the result of this. This is one of the things you, as researchers, are going to have to use a given parameter to work against. There are a lot of things that are going to impact this heavily, but that one man, the type of man who works for the battalion Command or squadron Command. His personality does impact heavily and it is a given.

NEW APPROACHES TO DECISION AIDING
FOR A NAVAL TASK FORCE COMMANDER

by DR. MARTIN A. TOLCOTT
Office of Naval Research

Traditionally, the design of a command and control system involves a series of well established procedures. First, a set of scenarios is generated, intended to represent the range of situations or contingencies in which the system is expected to function. Then, experienced military officers are asked to specify what information they would need in order to operate effectively - that is, to make decisions effectively - under those warfare situations. Often, they are asked to prioritize the information, and to specify some of the desired characteristics of each item, such as its tolerable delay time, its required accuracy, the form in which it should be displayed, etc. These data are then organized and summarized, discrepancies among the respondents are resolved through additional interviews or group discussions, and the resulting data are taken as the information requirements on which to base the system design. When compromises must be made due to limitation of equipment weight, space, cost or expected capability, they are based on the expressed priorities. Admittedly, this description is over-simplified, but it essentially describes how the information requirements are usually determined.

One of the problems with this approach is that there is likely to be a lag of 5-10 years from the time requirements are established until a system becomes operational. During that time many changes can occur, the most significant being, first, the emergence of new and unanticipated scenarios or contingencies, and second, the assignment of new personnel - new decision makers - with their own individual styles and priorities of information. Typically, command and control systems lack the flexibility to adapt to these changes.

I will describe an Office of Naval Research project, Operational Decision Aids, which attempts to provide this flexibility. It focuses on the decision process itself, and develops means whereby this process can be facilitated by techniques which take advantage of the experienced judgment of key decision makers in their actual operating situation . Although the project deals specifically with decisions made at the Navy Task Force Command level, the techniques being developed are potentially applicable to command/control systems at other levels as well. These techniques are expected to provide the flexibility needed to deal with unanticipated and widely varied contingencies requiring decisions to be made quickly, at sea, with imperfect or incomplete information; many of these decisions will have significant political implications. In line with this objective the Operational Decision Aids project is not attempting to determine information requirements for any specific system, but rather to develop and evaluate procedures for making most effective use of information already available - including the judgments of experienced officers. If the techniques work, they will help overcome some of the known human limitations in dealing with high information loads. These limitations include faulty memory, stubbornness about hypotheses even in the face of conflicting information, limited computational ability, rose-colored hindsight (that is, a tendency to remember past decisions as invariably correct), and narrowed focus under stress (that is, a tendency under stress to ignore information about low probability threats and to rely on habitual responses).

Our approach is to apply advanced technologies which have emerged from research in four scientific areas in ONR - decision analysis, computer science, operations research and organizational analysis. These technologies have all advanced far enough to have proven effective in certain limited applications. We are asking the question: can they be tailored to facilitate decision making in operational command and control systems? I will describe

briefly the concepts being explored in each of these areas.

Decision analysis is a formal procedure for structuring or modeling a complex decision problem into its component parts (which include choice points, chance events, and outcomes), eliciting judgments of experienced or cognizant individuals regarding their preferences or utilities for the various outcomes and their estimates of the likelihoods or probabilities of the chance events, and applying statistical rules for computing the expected value of each alternative choice. It is usually assumed that the decision maker wishes to maximize his expected value, although this need not be the case. He might, for example, want to minimize his maximum loss. The results of the analysis can then be displayed in various ways, to indicate, for example, how sensitive the results are to errors or changes of judgment, or how the likelihood of each possible threat condition changes as new diagnostic information is received, or when the threshold for a change of decision has been reached. I will not go into the details of this technique, since Dr. Kelly will describe it in a subsequent talk. However, I would like to make the following points:

1. Decision analysis procedures have been used with various degrees of success in many one-of-a-kind decision problems (such as evaluation of intelligence data, system procurement decisions, and development of decision rules for crisis situations). However, it is still a matter of controversy as to whether they will prove effective for Navy tactical decision making. Where they have been successful, they have required the presence of a decision analyst to help structure the problem and elicit judgments. We don't yet know whether the procedures can be programmed into a computer and carried out effectively by means of interactions between the command staff and the computer, and if they can, how long they will take and how much training will be necessary. We intend to answer these questions experimentally.

2. The triangle display which Dr. Kelley will describe is just one concept for displaying the implications of the commander's

judgments. We are investigating several alternative concepts, including one which displays risk.

3. Our objective is to provide an adaptable tool for Task Force Commanders. To the extent that these procedures impede rapid and flexible decision making, they will have failed to satisfy an essential criterion for tactical decision making, although they might still be valuable for other types of C^2 systems.

4. It may turn out that decision analysis is most useful as a training tool and as an aid in tactical planning. In those contexts it can help make commanders aware of the relative contributions of various diagnostic indicators in making inferences about a situation, and of the relationships between situation assessment, risk attitude, and action selection.

The second area of technology contributing to this program is that of information systems or computer science. Here we are interested mainly in data base management systems which can adapt to particular styles or preferences of individual users, and in simplified methods for people to communicate with the data base in both directions - that is, to insert requests for information, new instructions, and estimates or judgments to be used as data, and to receive effectively displayed representations of the current situation, warnings of predicted dangers, information triggers or alerters, and other data relationships as desired. The University of Pennsylvania is developing a system known as DAISY (Decision Aiding Information System) which embodies these features. It can keep track of the requests and decisions made by a particular user, call his attention to subsequent decision situations which are similar in nature, remind him of the information he requested and the decisions he made in previous instances, thus jogging his memory. It allows him to set alerting mechanisms for information he considers especially critical in a given situation, and to remove them at will. It allows him to set triggers for decisions he wishes to implement as soon as certain information is

received. And, it recognizes that, in general, 90% of requests are for only 10% of the stored data - but a different 10% by different users; utility files adaptively reorganize themselves to particular user requests, making the most wanted data most easily accessible.

The DAISY system is the furthest along in the program, and efforts are now underway to transfer some of these techniques to the Tactical Flag Command Center (TFCC) program currently under development by the Naval Electronic Systems Command.

The third technology area being drawn upon in this program is that of operations research or systems analysis. These techniques have in the past contributed methods for creating tactical models for a variety of purposes such as weapons or tactics evaluation, exercise reconstruction, war game assessments and the like. The idea here is that, with certain modifications, models such as these might provide a tactical commander with rapid estimates of the relative worth or outcome of several alternative tactics which he may be considering. To take an oversimplified example, if his objective is to lay out a course for a task force to transit from point A to point B, through an area with enemy threats in unknown but estimated positions, algorithms can be created to compute desired outcome criteria such as transit time and degree of vulnerability. If at some time an enemy submarine (for example) is sighted, new probability detection contours are computed and displayed, and the task force commander can quickly plot several alternative transit courses, and have computed and displayed the new values for transit time and vulnerability, so that he can make his own trade off in selecting a new course. Outcome calculators such as this (but much more detailed) are now being developed for air warfare operations and for electronic emission control tactics, both of which involve more variables related to own and enemy forces than can easily be dealt with mentally or on a scratch pad. The main challenges in developing this type of decision aid are:

1. To make sure that the models are detailed enough to help solve real tactical option problems, yet not too detailed to be irrelevant to task force command level decisions;

2. To ensure that the commander can insert his own approximations as to the tactical situation when appropriate, and quickly rule out certain obviously undersirable tactics, in order to enable the models to be structurally simple and functionally rapid.

This work on man-aided algorithmic solutions is not as far along as the other two areas described earlier.

Finally, a small part of the total effort is investigating the area of organizational analysis in the context of computer-based information systems. There is at least anecdotal evidence that the introduction of computer-based systems into organizations usually creates the need for reallocation of functions and corresponding re-structuring of the group in order to take best advantage of the new technology. Indeed, it is often the case that resistance aroused by the new systems and procedures seriously interferes with the realization of the potential benefits. Consequently, we are reviewing both the scientific literature in organizational theory, and the actual instances in which such systems have been introduced into military and industrial organizations. We are trying to identify any common patterns of organizational change which can provide guidelines as to desirable reallocation of team functions for future consideration in command and control.

In summary, we are not trying to design a new system. We are trying to exploit certain technological developments, tailor them to specific command and control purposes, and evaluate their potential effectiveness as aids to the decision process.

These techniques are designed to aid the decision maker rather than to automate the decisions. They make use of the uncertainty inherent in the situation by making it explicit - in the form of judged probabilities - and treating these probabili-

ties as data, rather than ignoring them. They provide aids to faulty human memory, through computerized recall and alerters. They facilitate the analysis of a decision problem in advance, and the establishment of decision rules for use later when speed is critical. They provide algorithms for rapid calculation of tactical outcomes, permitting evaluation of alternative trial tactics. They furnish a means for the decision maker to keep in mind a wider range of alternatives during the stress of battle when his focus usually narrows. And hopefully we will be able to provide guidance as to how the TFC staff might be structured for most efficient use of these techniques.

These aids, as they become available, are being programmed on a man-in-the-loop simulator and tried out with several typical battle scenarios to compare their effectiveness with what might be called a non-aided condition - namely, a condition in which data can be made available to the command staff as it is in current systems. We hope within a year to have the first set of performance data from these experiments, and then to be able to suggest which of these techniques are recommended for further development and application.

DECISION ANALYSIS AND DECISION AIDS[1]

by CLINTON W. KELLY, III
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The purpose of this paper is to briefly describe a research program designed to use the tools of classical decision theory to develop decision aids that can be used to assist military decision makers in near real-time. A corollary objective is to use the structuring of the decision process implicit in the development of such decision aids as a mechanism to train individuals to be better intuitive decision makers.

The motivation for this research on the development of decision aiding is a body of evidence which indicates that even in routine, unpressured decision contexts people are prone to many biases and errors of judgment (Reference 4). These tendencies toward suboptimal decision performance are further compounded under conditions of prolonged stress and fatigue, and in situations where decision makers are subjected to information overload, as is often the case in real-time tactical decision contexts.

The concepts behind the class of decision aids currently under investigation are relatively simple. Decision analysis provides a means of modeling a variety of generic decision situations to derive decision rules. These rules define decision thresholds as a function of the likelihood of certain key events which bear on the outcome of the decision. When a threshold is

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reached, the model implies that it is optimal to change from one course of action to another. Bayesian probability models drawing both on expert judgment and historical relative frequency data can be developed which provide a means of processing information as it arrives to yield time-changing probabilities for those events incorporated in the decision rules. These two concepts are displayed in Figure 1.

To illustrate the basic principles employed consider the decision problem described in Figure 2. The decision is whether or not to shoot at an approaching aircraft given uncertainty as to whether the aircraft is an enemy or a friendly plane. The details of this decision problem and the rationale behind the values and probabilities incorporated in the model and shown in Figure 2 are described fully in Chapter 1 of the Handbook for Decision Analysis (Reference 2).

There are basically three parts to such decision models: the formal structure of the decision; the value of each possible decision outcome, and the probabilities of the uncertain events which could affect the decision outcomes. The formal structure of the decision process reflects the relevant acts among which choice must be made and the events which could affect the outcome of that choice. In this case the choice is to shoot or not to shoot. Uncertainties are whether or not the aircraft is an enemy plane or friendly plane, and given the decision to shoot, whether the aircraft is destroyed or not. If the aircraft is an enemy aircraft and is not shot down, then whether or not it succeeds in its hostile objective must be considered. The second element of most decision models is a series of values, shown in this figure at the extreme right-hand side of the decision diagram, which reflect the decision maker's relative preference for one outcome of the decision or another given that for sure these outcomes occur. The rationale for assigning these values might be quite complicated and require additional submodels. In this case the procedure used to assign the values shown in Figure 2 was a form

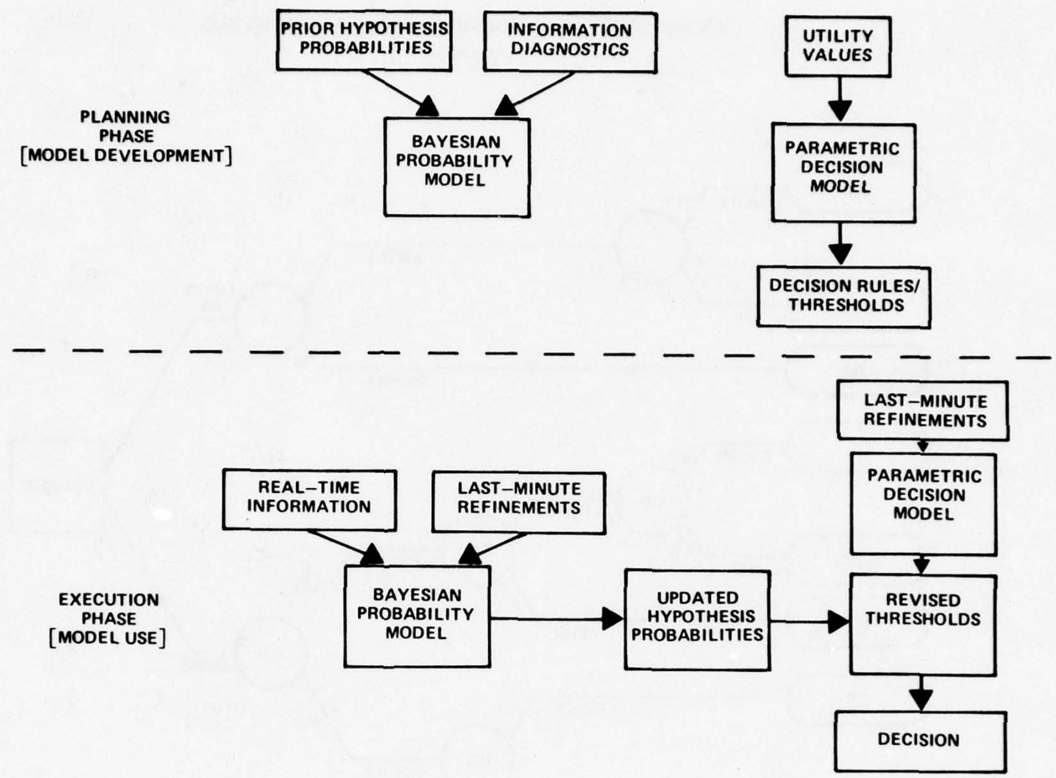

Figure 1
DECISION MODEL STRUCTURE

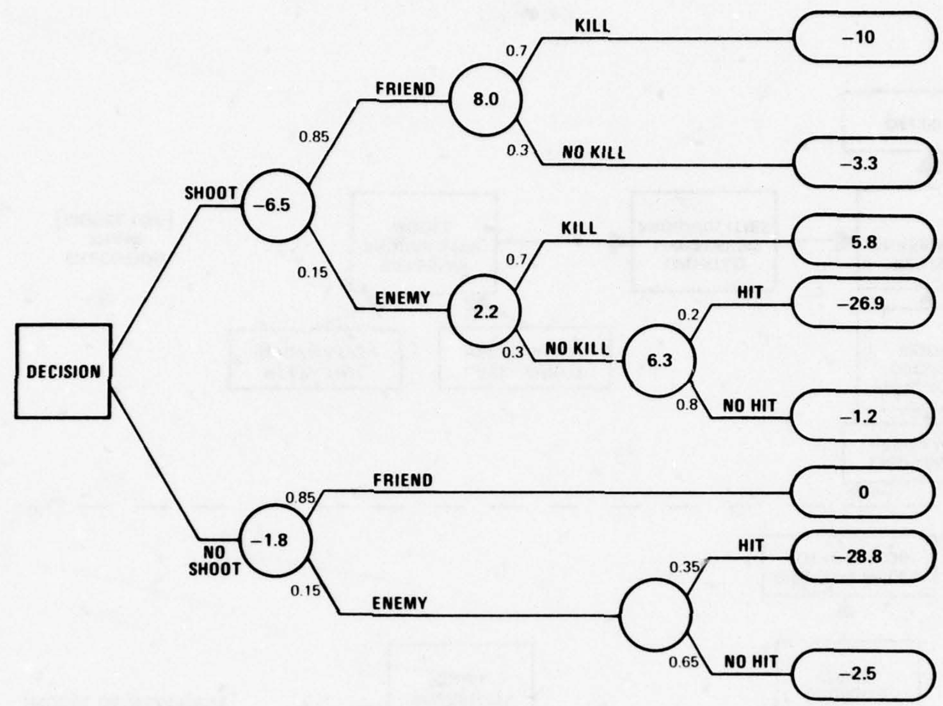

Figure 2
DECISION DIAGRAM OF AIRCRAFT ENGAGEMENT

of submodeling called multi-attribute utility theory (Reference 3). The third part of any decision model is the assignment of probabilities to those uncertainties which could affect the outcome of the decision. These probabilities are shown attached to the possible outcomes of each event in Figure 2.

Once probabilities and values have been assigned to the decision model, it is now possible to calculate for each course of action an expected value, which is a figure of merit that indicates the relative desirability of each course of action. This is done by computing probability-weighted averages of the outcome values. From the probabilities and values contained in the decision model depicted in Figure 2, it is apparent that the best decision is the course of action "don't shoot." This choice is affected by all of the inputs--some of which may be subjective and some objective--which are contained in the model. For example, it is clear that as the probability of the aircraft being an enemy is varied from the current value of 15% up to 100%, the expected value of not shooting will become increasingly negative and the expected value of shooting will become increasingly less negative.

Figure 3 shows the results of a sensitivity analysis done on the probability of the incoming aircraft being an enemy. Notice that when the probability of enemy is increased to a value of about 37%, the expected values of shooting and not shooting are equal and as the probability of enemy increases beyond 37%, the expected value of shooting is greater than the expected value of not shooting, indicating that for a threshold probability of 37%, the decision strategy should change from not shooting to shoot.

This determination of the probability threshold is an example of a decision rule referred to earlier. All of us are familiar with the informal decision rule "don't shoot until you see the whites of their eyes." The corollary rule in this instance would be "don't shoot until the probability of enemy exceeds 37%." It is apparent that this threshold will also be sensitive to changes in the inputs contained in the decision model. For example, if

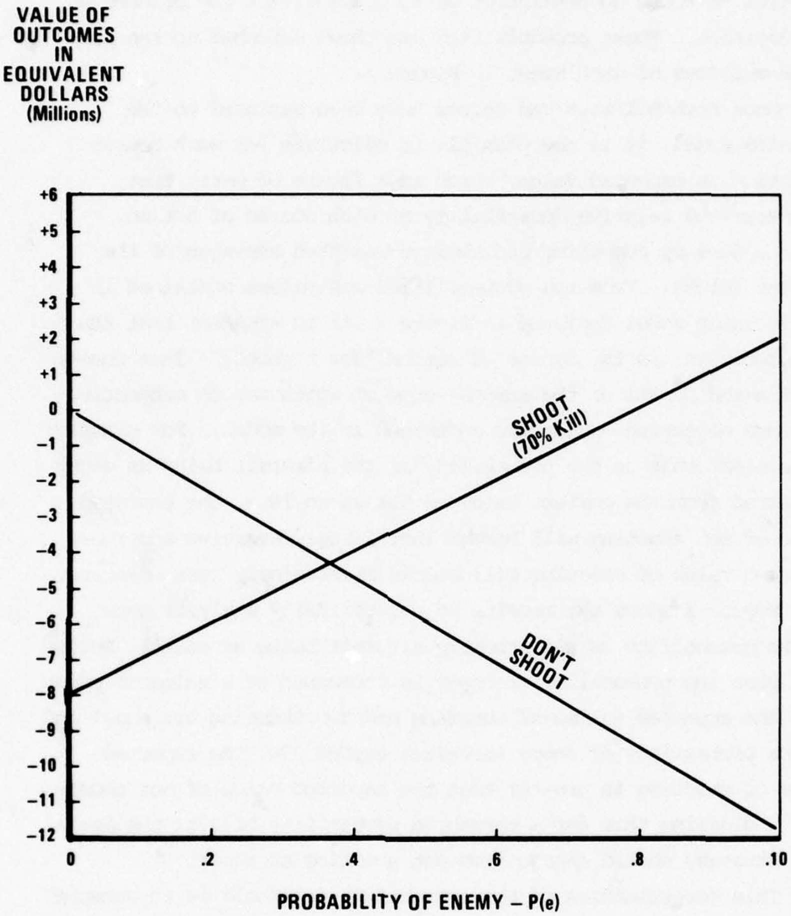

Figure 3
SENSITIVITY ANALYSIS OF AIRCRAFT ENGAGEMENT DECISION

the decision maker's preference (outcome value) is changed or if some of the other probabilities in the decision model are changed, then the threshold will vary. Thus, in many instances the decision rule should not only be conditional upon, for example the probability of enemy, but should also be conditional upon other inputs to the decision which may change with time.

Once a reasonable decision rule has been developed, for example a decision rule which predicates changing courses of action based upon the probability of enemy, then it is necessary to develop a probability model which is capable of transforming data about the tactical situation into a time-changing probability forecast as to whether or not the incoming aircraft is an enemy or a friend. Such a probability might provide for the inclusion of signals intelligence indicating whether or not an IFF signal has been received from the incoming aircraft, a visual sighting of the aircraft, and so forth. Obviously, the probability model will be more complex when the enemy threat is of major consequence. The decision aid would then consist of a mechanism to compare this time-changing probability with the thresholds established by the decision rule to identify that point in the evolving situation when the decision maker should consider changing his course of action. Such an aid should also display to the decision maker the rationale behind both the decision rule and time-changing probability.

The basic principles presented above have been used to develop a prototype decision aid that will be described in the remainder of this paper.

In the development of a decision aid, a key issue is a means of displaying the time-changing probabilities of events in relation to the thresholds that constitute the decision rule. It is possible to imagine decision-aiding systems in which the time-changing probabilities would be compared with a preset threshold by a computer, so that when the threshold was reached, some sort of signal would be provided to the decision maker. Such a system,

however, would lack several important characteristics that we believe are essential to any decision aid. First, it would not provide a decision maker with a means of extrapolating trends with respect to the time-changing probability and of intuitively estimating roughly when a threshold might be reached. Thus, there would be no basis for preparatory actions that may need to be accomplished by the time the threshold is reached. Second, such a system would pre-suppose that all of the relevant factors essential to a decision have in fact been included in the aid. The decision maker would then be placed in a position of having to accept this on faith rather than having all of the data and the implications of the data displayed so that he could evaluate for himself whether the key variables, as he perceives them, are in fact accounted for in the decision aid. Thus, the prototype decision aid which has been developed focuses as much on displaying all relevant information to the decision maker for his review and possible modification as it does on displaying the implications of that information for action selection.

For this decision aid, three principal displays are used. These are shown schematically in Figure 4. They include a primary action display in which the time-changing probability is compared with the decision thresholds, an intelligence display (likelihood table) in which the data that have been received and the implications of those data with respect to probabilities of concern are displayed, and a value display expressed in terms of the decision maker's relative degree of regret for various choices and their outcomes. The intelligence display provides the information which drives the time-changing probability, and the value display provides the information that is responsible for setting the decision thresholds.

The time-variant probabilities are shown by using a track or vector that moves in a triangular space. An equilateral triangle is used as a display, in this case, because it has the property that any point inside the triangle can represent three probabili-

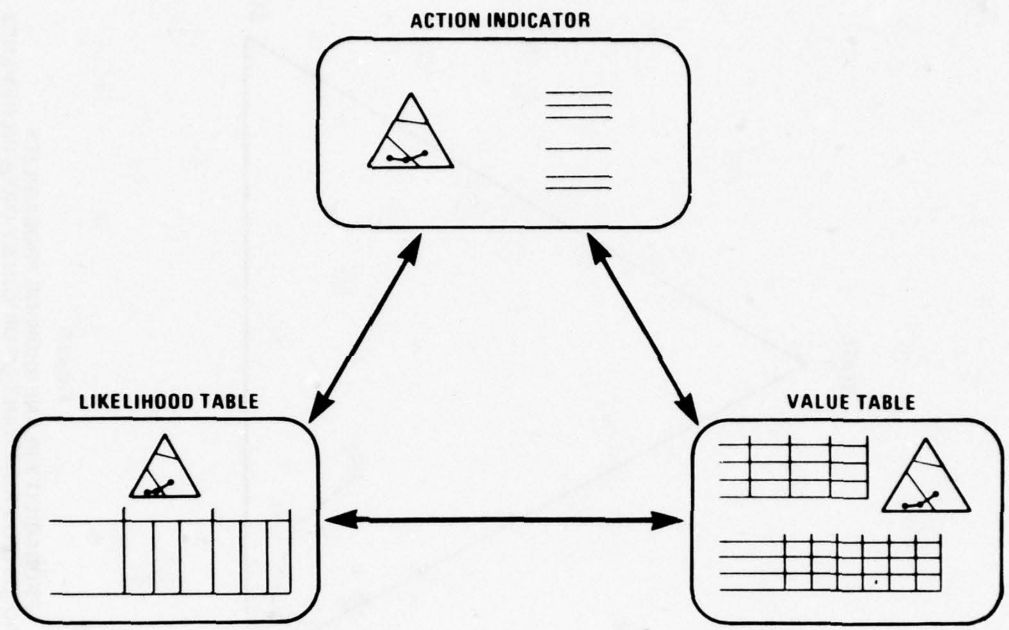

Figure 4
SCHEMATIC REPRESENTATION OF DECISION AND DISPLAYS

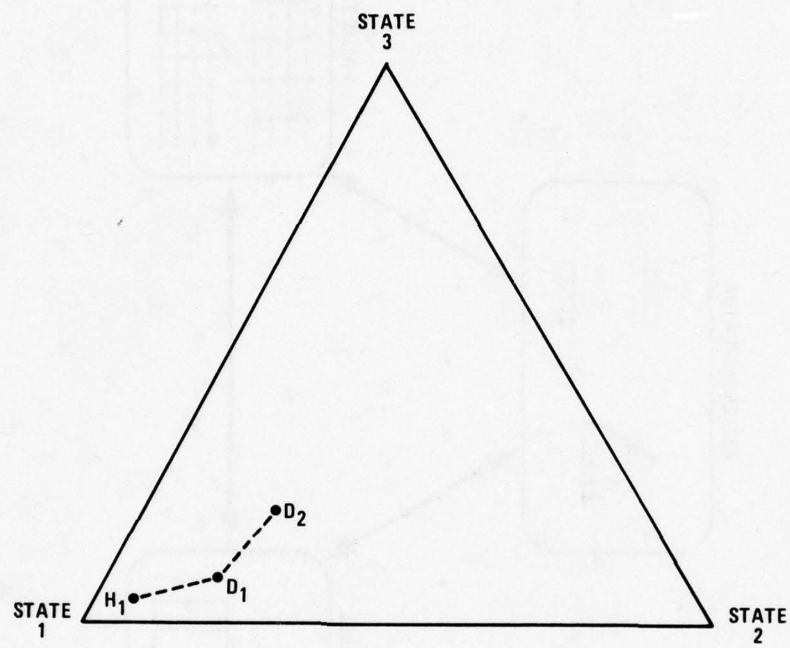

Figure 5

PROBABILITY PLANE SHOWING PROBABILITY
TRACK ADJUSTED FROM POINT OF ORIGIN BY DATA INCREMENTS

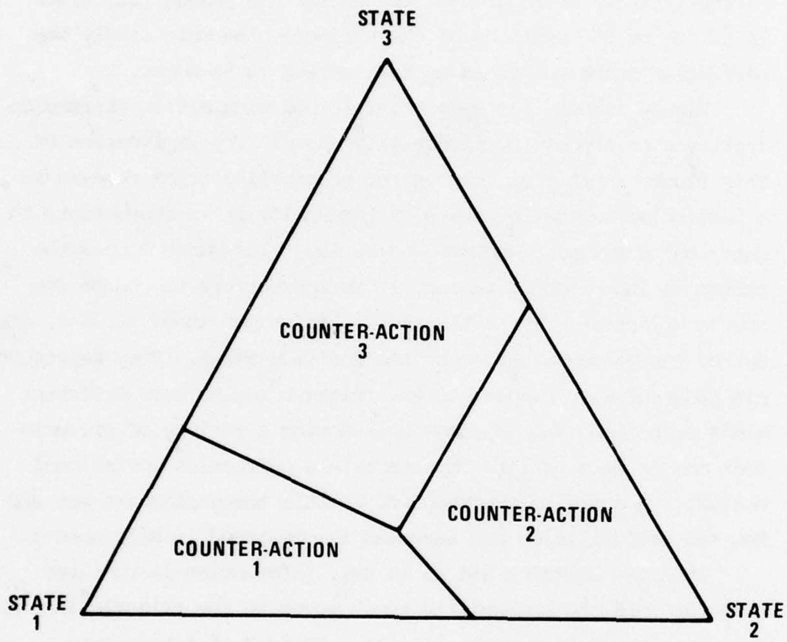

Figure 6
PROBABILITY PLANE WITH ACTION THRESHOLDS

ties that sum to 1.0. Thus, if one is dealing with an uncertainty that has three mutually exclusive and exhaustive possible states, the point in the triangle will represent the probability vector over those three states. An example of this probability track moving within the triangular space in response to changing information is shown in Figure 5. The closer the probability track is to one of the vertices of the triangle, the more likely the particular state described by that vertex is to occur.

Figure 6 shows the same triangle now with action thresholds overlayed on top of the probability space. The implication of this figure is that as long as the probability track remains in a particular region bounded by a threshold, it is appropriate to carry out one type of avtion; and as the track moves across the threshold into another region, it is appropriate to change the course of action. These thresholds, as we mentioned earlier, are set by the values assessed by the decision maker. They represent his judgment with respect to the relative regret over different kinds of actions and outcomes considering a variety of criteria that may be more or less important in a particular operational context. A detailed treatment of how the thresholds are set and how the probabilities are assessed is contained in Reference 1.

When the decision aid is in use, information is received over time and the probability track moves in the triangle in response to changing probabilities. Courses of action are recommended by virtue of the track crossing from one region of the triangle into another.

A wide variety of "what if" analyses are possible using this prototype decision aid, which again emphasizes that the role envisaged for a decision aid is that of an aid--a mechanism that would help extend the intellect of the decision maker and put structure to what otherwise might be a confusing situation, rather than a device which makes decisions according to pre-set rules that are programmed without any form of intervention by the decision maker. These "what if" analyses include the ability to

change the impact of different types of information that might be received, to postulate an occurrence that has not yet happened, to vary the importance assigned to different criteria, and to vary the cost of different kinds of errors. As any of these changes are made, the implications of the changes for action selection are displayed to the decision maker for his review. It is worthwhile mentioning that in this particular implementation of a decision aid, there is a formal probability model, called a Bayesian hierarchial model, that accomplishes the transformation of verbal and qualitative information into a probability distribution over the outcomes of concern. This model is presented in detail in Reference 2.

The preceding discussion has focused on situations where there has been but one key uncertainly--whether or not the incoming aircraft was an enemy or a friend or, in the case of the prototype decision aid itself, the principle uncertainty was enemy intent described in terms of three possible states. Imagine now a situation where multiple uncertainties are of concern. For example, in a decision as to when to launch an air strike (or other major action) against an enemy, we might be concerned with own-force readiness, with weather over the target area, and with enemy readiness. For a situation of this sort, we use a display consisting of multiple triangles, one triangle corresponding to each of the key uncertainties. Such a display is shown in Figure 7. This display has the interesting property that as the probabilities with respect to one uncertainty are updated, the probability track will move in that triangle and the thresholds will remain fixed. Because of consistency requirements which are imposed, the probability thresholds must therefore move in the other triangles. Correspondingly, if two or more of the uncertainties are updated simultaneously, then the probability tracks and the thresholds will move in each of the triangles.

Although the theoretical underpinnings of the decision aiding concept described above are sound and, by logical inference,

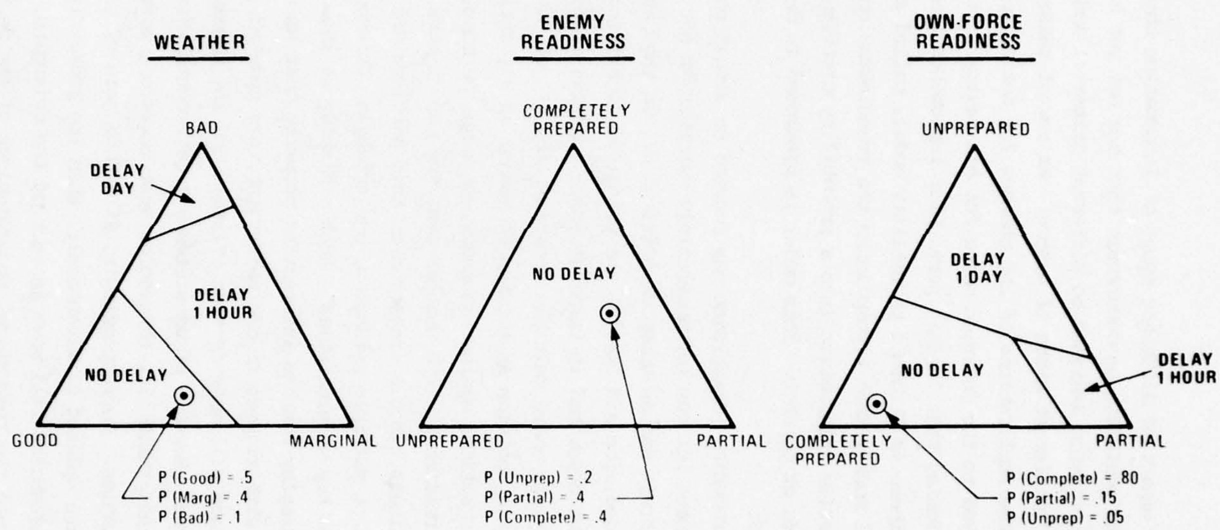

Figure 7

DISPLAY FOR MULTIPLE UNCERTAINTIES

should lead to improved operational performance in decision situations, the formal evaluations required to assess the applied utility of the decision aid have yet to be conducted. Plans for such validation work are now in preparation. An informal pilot project to help formulate a suitable validation plan, simulating tactical engagements while using the prototype aid, were conducted. At the anecdotal level, subjects generally thought the aid would be useful, with further refinements, as an on-line tactical aid. The subject's responses also indicated that the aid would be valuable as a training device to enable new task force commanders to become familiar with the tactical situation modeled in the decision aid, and to test alternative response actions in training exercises.

Clearly, additional research remains to be done to bring decision aiding concepts, whether the prototype aid discussed here, or others, to fruition. Beyond the obvious but difficult research issues inherent in the validation of this decision aiding concept, further research is needed to assess the utility of the concept as a training device, to determine the ability of people to process information derived from the multiple-triangle display, and to search for alternative display methods.

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* Currently under revision.

DISCUSSION

Otto Wech: Are you addressing directly to the Commander as operator or are you envisioning that the Commander interacts with the system by his staff:

Denicoff: Either way. From what we know of decision makers of that level, they tend to operate differently. They tend to use their staff differently. Some of them make extensive use of specialists and some of them like to get into details themselves.

Let me make one comment here, again I think we are trying to build in maximum flexibility. I very often here dogmatic statements in your direction. Namely the dogmatism says the Commander will never sit down and be terminal - utter nonsense. I have seen flag officers working at terminals and even get excited about that type of interaction. I think there will turn out to be as much variance as there are individuals. Some senior officers will always want to rely on staff members. Others will want to interact on their own. One premise I have is every time you have to use an intermediary - another person - there is some restriction, some inhibition. If we are going to have feed-back, and that if feed-back has to go through a second and third generation until it gets to its Commander, a hell of a lot is lost. So there may be a real gain in some instances of having direct interaction between various people and the data base. At lease we want to provide that capability that can be used or ignored.

Wech: At what level of steps do you determine the ability of the system to self adjust? Do you have control over that? Or is it a hardware or software given feature that you just take:

Denicoff: I would say we have two interests. One is to look at a particular configuration as a constraint on the world. Namely what is the best that can be done given that constraint? The constraint might be a hardware of soft constraint in the form of a system that has been posed. We must ask again, what constraints have been imposed by that system? How can those constraints

be alleviated given the restriction of that system? That's one goal. The other, I think, is a more research oriented goal, to end up with the specifications for the kind of hardware and software that has to be developed to make all these desirable capabilities possible. So one is to live with those real world constraints. The other is to write a specification to alleviate those constraints. You have both objectives.

Question: It seems that this process has a tremendous appetite for numbers and an underlying distribution. Will you say something about how you are going to obtain this?

Kelly: Well, actually I would argue that it doesn't have too big an appetite for numbers. The number of judgments required for the model I just described would take an experienced intelligence officer something on the average of two to three hours to prepare in advance and certainly no more than that. I might add that recently I had an opportunity to work on the problem that evolved in near realtime. We created a variant of this model and we were able to get the necessary input to both stage two and stage three in about two hours. That says nothing about the validity of the numbers and really what we are trying to do is find out if decision rules that are reasonably invariant can be identified.

Sacerdoti: I have a slightly related question here; how sensitive is the consistencies of those numbers and underlying models to be used because we will be dealing with different pieces of the problem at a time.

Kelly: It is rather hard to answer that without getting very specific. Some models are not very sensitive at all and in others it makes a tremendous difference. For example, in the illustration I used, you could vary the weight assigned to the different criteria over a wide range, or even drop any of the four value criteria and it wouldn't make any difference. In other models, of course, that is certainly not the case. I am sure there must be some underlying generalities, rules of thumb, we could use to help us make judgments of that sort, but we have not been able to

identify many of them at this time.

Bracken: In the model that you constructed, as I understand it, there are various actions available to Blue, certain probabilities of Blue taking those actions or perhaps adopting a mixed strategy.

Kelly: The model that we constructed purports to show that Blue showed do given uncertainty about what Red will do. It says little, if anything, about the likelihood that Blue will in fact take that direction.

Bracken: Well, let me ask the question in another way. How would you generalize this model if you were looking at things in a game theoretical context, where Blue had available to him some actions he might take with certain possibilities and Red did the same.

Kelly: One way is simply to say that the likelihood that Red is going to do something would be conditional upon what Blue chooses to do and you simply represent it in the form of a conditional probability. You run it out until sufficient time elapses so that carrying it beyond that point simply has no effect on the choices ou are faced with immediately. The simple little model that I described didn't have that kind of conditionality in it. Others certainly do. For example, the choice of whether or not to use certain tactical nuclear options in Europe would determine, to an extent, what the Warsaw Pact might do. If you look at that situation, you would work with probabilities that are directly conditional on your own choices.

Bracken: I think that a probability approach is called for here, not game theory.

Kelly: That is absolutely right. As a decision theorist I would approach it that way, not through game theory, although one might well approach it using game theory.

Bracken: Don't you think there are some inconcistencies?

Kelly: No, but I am certainly willing to be educated. I can't think of any inconsistencies - none come to mind.

Bracken: Well, if it's a sequence of simultaneous moves, then you don't get an opportunity to observe while you are moving. If it is a sequence of moves where Blue moves, Red moves, Blue moves, then you get a chance to observe, but if they are moving simultaneously...

Kelly: There is a difference between what one actually sees unfolding in the world and how one constructs a decision diagram that would help you choose a course of action today. You can certainly construct a decision diagram today under the assumption that the moves will be simultaneous and not sequential. In that case, of course, the probability, at least for the first stage moves of Red, will not be conditional upon what we do.

Bracken: What do you do then?

Andrews: I guess you would make an estimate of the situation based on the intelligence you have available. This may not seem to be a very satisfactory answer, but it appears to be the only one available.

J. Thompson: If you are saying to use a diagram such as you have indicated as an Educational Aid, I think these are useful. But if, as I understand, you are actually proposing this to be a decision aid in real time, in real world situations, I find it absolutely terrible! That is a tactic Commander who is going to be sitting in Washington watching a stochastic bug walking across a triangle which has probabilities which are very fuzzy and utilities which are very fuzzy. It seems to me very dangerous. Particularly since the CIA syndrome may tell him that as soon as the bug crosses the attack boundary, we should attack.

Kelly: I don't think it actually says that.

J. Thompson: Well, that is not what it says. It says, based upon the inputs and under these conditions, you should, in fact, prepare to attack and execute. Now, just as the trigger that Bob was talking about earlier in respect to Daisy is designed to evoke some kind of response from the decision maker, to that extent, this model does exactly the same thing. It is designed

as an aid, based upon the commander's perception of the situation, with some of the data put in ahead of time and some put in in real time.

J. Thompson: Not basically though, I mean it is the decision part and therefore it is a bit more than just useful information. I think your example about what things have been tried in business works pretty well. It points out a key difference between a military situation and a business situation. That is, nations can't take the bankrupt law. If you try something based on such and such data and such and such a utility function in business and you are wrong, you just take the bankrupt law and wait six months and you start over again. Nations can't do that.

Kelly: Well, let me answer that in the following way. You said this terrified you, but there is something that ought to terrify you more and that's a tactical commander trying to do all of this in his head by unaided intuition. The psychological evidence on this topic says that, our feelings to the contrary, people don't do as good a job as we may think they do.

J. Thompson: I am sorry, but I am willing to trust this to an experienced Commander. In certain situations he gets his information from the Secretary of State, maybe even the President. But you are really talking about a situation where Blue was the United States. This is an honest-to-God situation. You watch it in simulation. If I understand it correctly, the way you are talking about it in such a situation where Orange is the satellite state of Red and Blue is the U.S. Here is the Commander watching the little bug walking around instead of getting on the communications system and getting all the information he can from his subordinates and also from his superiors. I think that terrifies me a good deal more than anything that is in the head of one individual.

Kelly: The aid, of course, does not preclude the Commander from seeking information. In fact it is designed to help him identify

what information he ought to be looking for and can assist in the formidable task of integrating all that information. This notwithstanding, I think the concern you express highlights an extremely important issue - one that we are going to be evaluating during the next year. What I have presented is a tool. To the extent that it is used correctly, I believe it can be of use, and can be quite valuable. If you have someone who says, "Gosh, the bug crossed the threshold and therefore I am going to push the button," you have a misuse of this model. I think it is most important to keep the context straight. What we are talking about is a sophisticated aid - a clever version of a Commander's night order book, so to speak. Nothing really different, except for the implementation and the underlying framework, from the system used in the British Navy today. I share your concern because one of the things that bothers me is the possibility that people won't use this correctly. I do know enough about unaided intuition to know that there are some good decision makers and some bad decision makers. I think that for those that aren't as facile as others, something like this is probably a better alternative than muddling through without the aid.

Welch: Let me understand what you are saying here. It seems to me that one way to describe what you have there is a way systematically to mix current data with another set of data with a set of value judgments, of a set of logic connections, which you thought up prior to the event. For example, the logic tree and the different kinds of concern and the weight you put on those concerns. That, to me, seems to be considered data as well as anything else including the mission you are given among other things. It does seem to me one simple way to describe what you chooose to talk about is at least a systematic way of mixing current data on situations and post data.

Kelly: That is absolutely correct ad it might be thought of in another sense - as a way to integrate both the J2 and the J3

functions while preserving their integrity.

Bonder: It is a bit more than that Jeff. It does suggest that if one were "rational" one would act per the action space partitioning.

Kelly: Right. I am assuming that you have all the risk and every thing else included, much of which I didn't even talk about.

Bonder: There is an action space there that is divided and it is divided based on beliefs and certain assumptions made by a great mathematician a few years ago. The tree folding back is based on some logic that is some set of assumptions about how one folds back trees. One folds back trees that way if you believe the "assumption" on how to fold back trees. I am not saying they are right or wrong. I am just saying there are explicit rules on how to fold back trees. All I am saying is the Commander should know he has certain transitivity kinds of beliefs about the world before he should say, "I see that kind of space, I'll that way." You all know what I am talking about I think, insofar as what axioms I am referring to. If he believes in it, fine. If he doesn't he ought to think about it a little stronger before he says something. It is more than just a data basis. It is a decision making logic that is considered to be rational if you believe in a certain set of axioms. All I am saying is a Commander should know what they are if he wishes to follow that kind of prescription.

George Pugh: I think the thing that bothers me most about the decision aid is the underlying assumption that you conditional probabilities are constant. I understand that the user puts the conditional probabilities in on the assumption of various scenarios that he thinks of as possible alternative enemy courses of action. If a different set of scenarios begin to unfold, he might have wished he had put in different conditional probabilities. My question is: Do you have in mind some way of testing the probable constancies of the conditional probabilities in some sort of situations?

Kelly: What we are doing now is looking at a variety of scenarios using the same framework and simply trying to get a feel for the extent to which these probabilities change, and what characteristic of a scenario is responsible for the change. This then should lead us to a variety of updating and interpolation methods.

REMARKS ON THE PRESENTATION GIVEN BY DR. CLINTON KELLY

by J. R. THOMPSON
Rice University

If the "decision aid" suggested by Dr. Kelly were simply an educational device, I should not be excessively disturbed. But he has made it clear that his model is to be used in real time tactics against Russian vessels. I find this simply terrifying. The possibility that a commander in a crisis would spend his time watch a stochastic bug walk across a decision triangle, ready to push a button if the attack boundary were crossed, has a hybrid Rube Goldberg-Doctor Strangelove flavor. The input to the "aid" is of necessity extremely noisy--both in terms of the relevant probabilities and utilities. The brain of an experienced commander is far better suited to the complex task of decision making in the situation described by Dr. Kelly than any systems analysis "aid" yet devised.

Moreover, the existence of such an "aid" would provide a dangerous temptation for a commander to use the black box instead of his own judgment. Consider the case where the commander pushes the button when the bug crosses the boundary. Whatever the negative result might be (including a war) the commander could in any subsequent court martial make an authority appeal to the "aid" as to a "suggestion" from a superior officer.

One of the reasons why management science procedures frequently are inappropriate for military decisions is the fact that there is no bankruptcy law for superpowers. If a business uses such a device as that suggested by Dr. Kelly and the decision advocated is wrong, the worst that can happen is that the firm is forced into bankruptcy. The members of the firm may then reincorporate and try again. Thus, the riskiness of decision making in business is not of the same kind as that experienced in military situations.

ADVANCED DATA PROCESSING CONCEPTS FOR NAVAL TASK FORCE DECISION MAKING

by MARVIN DENICOFF
Office of Naval Research

This talk is directly related to Dr. Tolcott's paper; it provides an extension in the Information Systems area to Tolcott's discussion of Decision Aids for Naval Task Force Commanders.

More so, perhaps, than any other field, advancement in computer science is frequently contaminated or marred by exaggerations of the true state of development. For example, while considerable progress has been made, it is simply not true that decision makers can routinely avail themselves of such desirable computational tools as: on line-real time interrogation of stored data, written or spoken English language interaction with computers, extensive use of management by exception principles. These features certainly are among the most frequently described goals of modern management support systems; yet, we have stated the objectives so forceably as to fail to make careful descriminations between truth and myth, reality and fiction.

The Office of Naval Research Operational Decision Aiding Project (ODA), described by Marty Tolcott, has among many interests, the goal of capturing for the Task Force Command level the latest progress on computing science while providing a laboratory facility for testing the readiness and appropriateness of advanced computer concepts to command and control requirements. Along with such always desired front ends as real time and natural language interaction, ODA is concerned with evaluating data base management systems and information storage techniques which must be operational if our sexier, more visible prescriptions for curing C^2 problems are to have any impact.

In the ODA context, the University of Pensylvania's Wharton School is the ONR contractor responsible both for developing C^2 computational aids, and for creating the general computational test facility essential to evaluating decision science and operations research methodologies as well as information science technuqies. My talk today will be limited to a description of the Wharton School's role in defining and making ready for test a set of near term computational aids which, in their view and ours, seem applicable to the C^2 Task Force situation.

Let me begin by underscoring that the University of Pennsylvania work on C^2 results from three years of previous ONR basic research funding on designing concepts for coping with large data base problems. Building on their own efforts in this area and that of other ONR contractors (Cal Tech, SRI, and University of Illinois), Penn made a conscious selection of those research results which satisfied the conditions of being: (1) most ready for test, and (2) most suitable for C^2. While the test program will not get underway until claneder year 1977, Penn has already begun to establish a computational test facility that includes PDP 10 & 11 computers; interative terminals; large and small screen black and white and color displays; and such mechanisms for interacting with display as the lite pen, the track ball, and the electronic mouse. To these assets, the completed facility will add: (1) C^2 decision models and algorithms for test and evaluation, (2) human subjects, (3) an experimental design plan, and (4) a methodology for cost/effectiveness measurement of test results. Additionally, the test facility operation includes C^2 scenarios which are approximations of real world conflict situations, and a rich, live data base descriptive of US and enemy naval forces, and geographic and environmental conditions for a "mythical" part of our modern world.

Now I would like to turn to a brief discussion of the initial set of computational aids already programmed by Penn for later evaluation in the test facility. These aids may be divided

into two categories; front end representing mechanisms to improve man's facility and options for interacting with computers; and back end descriptive of techniques for storing and retrieving data in a real time decision environment.

Among the available front end computer aids is a natural or English language interrogation capability. Questions must be typewritten; no speech interaction made is currently contemplated for ODA. The natural language, system, modeled after a development at Cal Tech, permits questions to be asked of the C^2 data base in a restricted form of English. Permissable are such questions as : (1) which ships in the data base are configured with a designated radar or sonar?, (2) What is the maximum speed of a particular ship or aircraft? or (3) What are the operational characteristics of a specified weapon? Interrogation is restricted in that the use of synonyms is severely limited; further, the size of the English dictionary and relationships across data fields is constrained. The just described English language processing system includes a fairly sophisticated spelling corrector. More advanced natural language systems are beginning to emerge from the basic research program and will be considered for later incorporation in the ODA Project.

A concern of natural language interactive capability, given the present state of the art, is the imposition on the user or manager to learn a formal grammar or computerize. This grammar or rule book (protocols) must be memorized and employed explicitly if serious errors and "hang-ups" are to be avoided. Among the unanswered questions and ones to be tested by ODA are whether management will make the investment to familiarize itself with the complex syntax of computer interaction, and whether such interactive complexities will hold up and work under battle stress. An alternative to an English language interactive mode is a touch screen or menu display system; this too to be evaluated in ODA. In this case, decision options are displayed on a screen; the user points to or keys in a desired choice and he is led inevitably

to particular display refinements directly reflective of his concern.

As now contemplated by ODA, the test program will include the English language interrogation capability, a touch screen mode, and an option mixing touch screen with limited typewritten English language input.

To the further interest of displaying computer output, Penn has designed a screen segmentation or split window concept. The screen segmentation concept contrasts with an alternative of multi screen displays. In the current Penn design, the C^2 display is divided into five parts; each part having a unique scrolling capability and a capacity for being treated as though it reacted to our was controlled by its own separate computer. While the present design is a fine segment screen, it is important to note that the raw capability now exists to decrease or expand from a human engineering standpoint. To add to your information base, the contemplated fine segments will be used for: (1) displaying inputs or interrogations framed by a particular user, (2) showing outputs, results of models, and answers to questions, (3) displaying messages/message traffic tailored to each user, (4) indicating the assignment and realization of "alert or alarm" conditions appropriate to the C^2 situation, and (5) establishing a time clock or date/time stamping of all computer interactions.

The design and ultimate testing of an "alerting" capability is one of the most exciting Wharton School software packages available for ODA. To appreciate the potential utility of an alerting or triggering mechanism, one has only to reflect on the passive nature of the best available computer systems on the market today. Their vast potential for response - even with optimal storage and search algorithms - has very much a dormant orientation. Only to the degree that the right questions are asked by the right person at precisely the right point in time does this passive interactive capability support the decision

maker's requirements. An alert capability, in contrast to passive management support systems, is a concept wherein threshold or alarm conditions, initially assigned by knowledgeable C^2 commanders, are continually machine monitored and compared with the dynamic, incoming data stream. Alert or alarm thresholds (representing a manager's anticipation of an impending or potential crisis situation) might include such eventualities as the buildup of enemy forces in a given zone, excessive downtime of friendly aircraft, projected unavailability of logistics resoruces, etc. Satisfaction of a predesignated threshold situation can, in the Penn design, be communicated to the interested user through such devices as terminal print-outs, print-outs augmented by flashing lights, the sounding of bells or buzzers, changes in the color of window displays, or the computer generation of human sounding speech vocalizing the typewritten alert message, or calling out a warning signal. The described alert capability permits the individual user to dynamically set, shut down, or reset thresholds. Penn has also created a feedback mechanism which --- on request--- could inform the user on algorithms and data supporting the alarm sounding, and could report (through directed memory search) on previous actions taken by other managers faced with the same or similar alert situations.

Supporting, driving, and facilitating the realization of the described front end man-machine interactive capabilities is the need for software to ensure the efficient storage and retrieval of data. Certainly, system responsiveness ---- independent of how responsiveness is defined --- is directly dependent on such issues as the speed and completeness with which desired information can be delivered. Penn, utilizing techniques from its own basic research program and borrowing from others, has put together some innovative software ideas for the ODA C^2 test program.

The first concept that I will describe is the automatic creation of "utility files." A utility file is defined as a ten or fifteen percent subset of a total file which accounts for 85

to 90% of the interrogations. The computer, by continuous monitorship of the interrogation stream, defines and selects out for special storage those data which, in fact, are most frequently called for. Past assessments of logistics and C^2 decision systems underscore the given statistic that the vast majority of user questions are repetative, and can be answered by a small fraction of the full file. A significant speed-up in information retrieval is possible given a system which automatically recognizes and organizes data in cognizance with this phenomenon. Interrogations are directed to the mini file rather than incur the costs of runs against the expanded data base.

The speeding up of response is also a promise of Penn's design of a Data Base Management System (DBMS) which employs notions taken over from recent developments in "relational" data file formatting. In this case, the user can, for example, more instantaneously up and down a hierarchal chain of system relationships, eg., a task force designation, ships and aircraft assigned to the task force, major systems related to the ships and aircraft, equipments contained in systems, components contained in equipments, and parts embedded in components. The user can ask for and get quick response to such questions as: (1) List all ships for a particular task force, (2) List all ships for the Task Force on which a designated radar is installed, or (3) Provide a list and count of each radar type on a designated task force. Conventional file storage techniques require an exhaustive search of the total ship/aircraft configuration file to provide answers to questions of this kind.

Lastly, Penn's DBMS has an adaptive, automatic capacity for reconfiguring data across such "speed of retrieval" sensitive storage media as core, disc, drum and tape. This reconfiguration process, affording still one more opportunity for improved computer responsiveness, organized and reorganizes files based on such factors as the use of statistical algorithms for automatically characterizing the interrogation load, the employment of season-

ality and smoothing factors, and the incorporation of human set priority overrides.

In closing, it should be emphasized that the described capabilities, while available, have yet to be tested for their applicability and suitability to the Task Force C^2 environment. The primary purpose of the Operational Decision Aids Program is to provide quantitative and quatitative measures of the cost/efficiency tradeoffs across aids, and to explore human factors issues prior to real world implementation.

To end on a positive note, it appears that computational capabilities already on the shelf make possible the dream of tailoring computer system to sent individual needs and whims. The range of possibilities includes interrogation by natural language or menu selection, the personal designation of alerts or thresholds, split screens whose contents almost magically adjust (messages, alerts, etc.) at the call of each user, color coding or sound signals as unique output or personality designators. Whether this potnetial capacity for both having our cake and eating it well prove to be too rich for the C^2 blood stream is an important question for ODA. Fortunately, we are designing the ODA test bed to answer it.

ADAPTIVE COMPUTER-AIDED DECISION SYSTEMS

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Introduction Most systems for command and control have as their central purpose the facilitation of tactical decision making, and today, tactical operations are becoming increasingly sensitive to decision making quality. Large stakes rest on the ability of personnel to request and to process volumes of information, and to make rapid and effective decisions. Often, the decisions are made sequentially, and the consequences are likely to affect future choices. Pertinent examples are found in a variety of military and non-military systems. Among these are anti-submarine warfare (ASW), anti-air operations, shipboard tactical operations, coordination of electronic warfare (EW), control of remotely piloted vehicles, environmental surveillance, crime prevention, and air and highway traffic control. All of these application have in common changeable *decision environments, frequent decision* responses, copious but fallible information, and a minimum of time available *for off-line* aids.

The human decision maker (DM) generally performs sub-optimally under such conditions. His behavior is typified by cognitive limitations on memory, attention and processing, and biases and inconsistencies in aggregating information. Accordingly, computer aiding techniques have been developed to improve performance in many of these areas. Computer aiding can unburden the operator of routine computational tasks, assist in structuring the decision, perform probability assessments, and call attention to critical events. In general, these techniques have been applied to static, well-defined decision situations, using off-line modes of interaction.

More appropriate for the tactical case, however, is use of the computer to respond to the human during the decision making process itself. This type of interactive participation requires computer adaptation to changing task requirements and operator needs. Also, the frequently subjective, incompletely quantified nature of real world decisions may necessitate the incorporation of some form of a trainable model of the human decision maker, in order to determine his preferences and goals. Overall, adaptive computer programs can provide:

(1) Generalized goal-directed system behavior in environments which cannot be predicted in advance,

(2) A functional structure for modeling processes which cannot be defined analytically, but which allow directed training for optimal response,

(3) Automatic system performance improvement as a function of experience,

(4) Quick adaptation to immediate changes.

Adaptive Aiding Concept Figure 1 illustrates the generalized form of adaptive decision aiding systems investigated by Perceptronics over the past five years. The upper part of the diagram shows the usual control loop of the human decision maker. He or she processes decision information, presented on some form of display, and makes choices which both affect the decision environment and alter the information available for the next decision. The aiding system, resident in a digital computer, has as its input the same decision information available to the human operator, as well as the decisions made by the operator on the basis of that information. Using adaptive programs and normative decision criteria, the computer builds a decision model of the decision maker, and, by means of interactive display programs, provides the operator with on-line recommendations based on his own preferences and decision strategy. Later, for evaluation or training purposes, the computer provides a performance report, in which decision making effectiveness can be separated from the actual, probabilis-

tic consequences of the decision.

Concept Implementation A decision support system termed ADDAM (Adaptive Dynamic Decision Aiding Methodology) was developed in accord with the above concept. ADDAM consists of an adaptive decision model which continuously observes both the decision environment and the DM's behavior, learns his decision policy, and makes decision suggestions based on the apparent value of the alternatives to the decision maker. In the present case, the modeling technique is based on the prediction of decision behavior according to maximum expected utility (EU) strategy. In simple terms, expected utility is calculated by multiplying the subjective value (utility) of a decision outcome by its probability of occurrence. Previous investigators have shown that the EU model is robust, and adequately represents human decision behavior in a variety of circumstances.

The adaptiveness of the ADDAM system is realized through the use of a trainable multi-category pattern classifier. As the DM performs the decision task, this on-line estimator observes the operator's choices among the various decision options. The estimator, using event probabilities as inputs, attempts to classify these probability patterns by adjusting utility weights according to an adaptive error correcting algorithm. In this manner, the utility estimator tracks the operator's decision making and learns his utilities. Such an approach has a number of advantages compared to off-line utility estimation. Dynamic estimation observes and models actual behavior rather than responses to hypothetical decisions. It does not interrupt or intrude on the process of decision making. And it responds to ongoing changes in task characteristics and operator needs.

Probably the easiest way to describe the utility estimation procedure is by example. For instance, a key application of ADDAM is in intelligence gathering. Here, the dynamic utility estimator, shown schematically in Figure 2, classifies pattern vectors

$$\overline{P} = {}_1p_1, {}_1p_2, \cdots {}_kp_i \cdots$$

whose components, ${}_kp_i$, are a function of the probability that an object of type i is present and the reliability k of the sensor used to detect it. These probabilities are weighted by the corresponding utilities ${}_kU_i$ of object sensing. The discriminant functions are then the expected utilities of each sensor decision. The utility estimator computes the EU of each sensor at each field location and selects that sensor at each location for which the EU is maximum. The sensor selected at each location is compared with the actual selection made by the operator, and if they differ, the appropriate utilities are rewarded (increased) or punished (decreased) by the training procedure. Thus the utilities are trained to characterize the operator's judgmental behavior -- i.e., to make the utility estimator respond with the same decisions as the operator. A more detailed explanation of the learning algorithm and its underlying assumptions may be found in Davis, Weisbrod, Freedy and Weltman (1975).

The characteristics of the dynamic utility estimator have been evaluated in *decision contexts which include a simulated* fishing fleet surveillance task (Davis, Weisbrod, Freedy, 1976), and currently, a simulation of anti-submarine warfare. In all of these applications, the estimates of multiple dynamic utilities typically converged rapidly to stable and distinct values. A representative example of the behavior is given in Figure 3. Here the number of utility adjustments per decision is graphed as a function of decision cycles for a specific utility. Initially each decision results in a utility adjustment. Eventually, adjustment is made only about one in ten decisions. There appear to be two stages in machine adaptation: (1) a rapid stage, in which the major protion of adaptation is made; and (2) a gradual stage, during which few adjustments take place, and the machine approaches systematic behavior. In this typical case, major

adaptation was completed after only about five decision cycles.

Of course, convergence to stable values is only useful if these values are accurate in predicting operator decisions. ADDAM has been found to be quite effective in prediction, with accuracies ranging from 75% in the computer aided training task (May, et al, 1976) to 95% correct predictions in the simulated intelligence gathering task (Davis, Weisbrod, Freedy, and Weltman, 1975). Additional evidence of applicability was seen in the high correlation (.82, $p<.01$) observed between model-estimated and operator-expressed preferences in the intelligence task (Weisbrod, Davis, Freedy and Weltman, 1974).

ASW Simulation Study Analysis of the ADDAM system, and of its potential applications, led to a variety of questions requiring experimental validation. Does model-based aiding actually work in practical situations? Are operators able to exploit the aiding given them? Is the aiding primarily effective in improving decision rate or decision quality? These and other questions formed the basis of a full-scale experimental study. The investigation was organized around a realistic ASW task simulation, highly evocative of actual submarine localization and tracking. The simulation derives directly from the salient features of ASW localization and tracking. The operator's task represents an attempt to capture the decision making processes and dynamic flavor of the ASW situation, while retaining some degree of experimental rigor.

In brief, the simulation involves a single ASW operator, much like the evaluator in a shipboard CIC. His task is to track the movements of a hostile submarine and, less critically, a non-hostile mobile object (a whale) as they move in the attack zone preceding an aircraft carrier. The attack zone is formed by a 5 by 5 grid, where each grid element represents approximately 2.5 nautical miles. Neither the operator nor the computer aiding system are able to observe directly the movements of the submarine and whale. Their only access to the environment is through

sensors which the operator deploys at selected grid locations. These sensors differ in their abilities to detect different types of objects, in their reliability, and in their cost. A helicopter, for example, can only detect a floating submarine, and has high reliability. A destroyer can detect any type of object, also with high reliability, but is more costly to use. Five different types of sensors are available in all.

The operator is asked to monitor the movements of the ASW target elements and to report their locations. To accomplish this, he deploys the available sensors, reads their outputs, reports the status of the tracked objects, and receives the probabilities of their next location, which he uses to make his next round of sensor placements, and so on. He can also receive decisions aiding generated by the ADDAM system. Figure 4 schematically diagrams the flow of information between the DM and ADDAM. The upper loop represents the main flow of task information. The external organization block represents the information the operator brings into the task, i.e., his available sensors, "textbook" ASW startegies, organizational priorities, etc. Movements of the submarine and the whale, the results of sensor deployments, and production of the probability information is controlled by the real-world simulator program, which combines conditional action probabilities (supplied by "experts" on submarine and whale behavior) with monte-carlo selection to provide a continuous stochastic and believable ASW scenario.

The lower loop in Figure 4 contains the decision modeling and aiding functions. The operator's sensor deployment decisions and the intelligence report are automatically input to the decision model, as previously discussed. At the experimenter's option, the DM receives decision aiding from the model. Three types of decision aiding report are generated by ADDAM during the course of a decision cycle. They are described below in accord with their order in the task sequence.

(1) Intelligence Report. This report is derived automatically from the operator's status report, and from "expert" assessment of the behavior of these types of objects. ADDAM assumes that the operator has correctly reported the location and heading of each object, and, by aggregating the conditional probabilities of state transformations, makes a Bayesian estimate of their next location. The intelligence report presents the (non-zero) probability that an object will be in a sector of the attack zone.

(2) Sensor Output Evaluation. This report has the same form as the intelligence report. However, the probabilities are obtained by using the actual sensor outputs, active or non-active, to update the intelligence report probabilities according to Bayes' Rule.

(3) Suggested Sensor Placements. This report is based upon the adaptive estimates of the operator's utilities for information received from each type of sensor. It consists of sensor deployment suggestions which maximize the evaluator's expected utility for information gain.

One of the advantages of using an adaptive decision model as the basis of decision aiding is the extensive performance evaluation it makes possible. Two important types of performance measures are directly obtainable. These may be termed (1) decision outcome measures, indices that monitor actual decision effectiveness, and (2) decision quality measures, reflecting the logical soundness of the actions prior to bcserving the consequences. Both types of measure were employed in the present study.

Decision Outcome Outcome measures are the ones typically used in evaluation of system performance. Their purpose is to define performance in terms of objective, readily-available criteria of cost and achievement. They focus on the actual outcome of an exercise, and include such variables as speed, accuracy, error rate and type, costs. etc. In the present case, the basic per-

formance score was defined as:

$$Score = Gain - cost$$

where

$$Gain = Points - Penalties$$

Points were credited for correct location reports, and *Penalties* were deducted for incorrect ones. *Cost* was the cost of sensor resources allocated. Operators attempted to maximize their score; score feedback showed them how they were doing throughout the test session. An additional outcome measure was decision throughput, defined as the number of decision cycles completed in a test session.

Decision Quality In the long run, outcome measures are the true criteria of performance. But while they indicate the actual amount of goal attainment, these external measures seldom identify the specific, short-term deficiencies of behavior. Quality measures are used to evaluate the standard of decision making regardless of outcome. This is done by means of normative criteria which classify the decision according to the expected outcomes of the chosen actions. Such performance measures are extremely valuable, because in aiding, one wishes to focus on the decision before its result is determined by the probabilistic outside world (Nickerson and Feehrer, 1975). In some cases, correct decisions have poor consequences, while poor decisions have good outcomes. The main quality measure used in the present study was deviation from maximum expected utility (DEU). The expected utility of a decision is composed of the probability weighted utilities of its possible outcomes. If the probabilities and utilities involved are accurate, the DM can do no better than pick the alternative which yields the maximum expected utility. Complete self-consistency seldom occurs,however, and even though a decision maker exhibits a stable preference structure, any randomness of behavior will result in a proportion of decisions which are suboptimal. The extent of suboptimality may be measured by calculating the average difference in expected utility

between the optimally derived and the actually chosen alternative.

A group of twelve operator subjects participated in the study. They came from the local Air National Guard center, were equally divided between CO's and NCO's, and were well representative of military personnel who might interact with future computer-aided command systems. Half were assigned to an aided group and half to an unaided (control) group. Unaided operators worked alone, using only the computer-generated intelligence reports during task execution. Aided operators received additional computer assistance in the form of sensor output evaluation, and sensor placement recommendations. Following two practice sessions, during which the operator's utilities were learned by the aiding system, performance was recorded in a 1-1/2 hour test session.

Table I summarizes the experimental results. The data showed that the aided group performed significantly better than the control group ($P<.05$), improving their mean score by almost a factor of two (88%). Improvement was partially attributed to a small but significant increase in the number of decision trials completed during the session. But most of it appeared due to the better overall quality of the aided decisions. That is, the aided operators incurred slightly higher sensor costs, but received a much greater return in points, and a substantially lower number of penalties. Decision consistency, as measured by mean deviation from maximum expected utility, was also significantly ($P<.05$) enhanced for the aided group.

It is interesting to note that besides obtaining almost twice the score of the control group, the aided group displayed considerably less variability among subjects. This intersubject consistency is evident from the difference in standard deviation (40.2 aided versus 64.9 control) and appears even more pronounced when the coefficients of variation are compared. The coefficient of variation is defined as 100 times the standard deviation divided by the mean; its purpose is to normalize for the size of the mean. The calculated values are 24.9 for the aided group versus 132.8

for the control group, representing an imporvement ratio of over five to one.

Conclusions The combination of probability aggregation, adaptive utility modeling, and normative decision recommendation described here appears well suited to the complexities of tactical decision aiding. As implemented and evaluated in the ADDAM system, these techniques responded to differences in decision style and to changes in task circumstances, they supplied a variety of aiding information, and provided a framework for analyzing and communicating the rationale for decisions to the decision maker. All in all, the adaptive system became an interactive "staff aide" to the decision maker. As such, it was accepted without problem by the operator subjects, in great part because it actually reflected the individual's preferences and style.

Much of the significance of this work lies in its incorporation of both descriptive and normative aspects of decision analysis into a single system. The descriptive modeling is internally validating through prediction of behavior, while the normative recommendations represent a processing of new inputs in accord with the same previously observed behavior. Thus, the operator's decision policy cannot only be captured and analyzed, but can be used to systematically reduce some of the cognitive effort of processing new problems. Operator consistency tends to improve, since the aiding system incorporates a more representative sample of behavior than the person normally considers, and actions are structured more carefully, according to optimal rules. Finally, the technique is computationally parsimonious. Only those structural aspects necessary for capturing the operator's behavior are included, much as pattern recognition techniques normally require only a small portion of the structure required by complete dynamic models.

Analysis indicates that the domain of greatest promise for adaptive decision aiding lies in areas of high time and load stress, where there is a reliance on changing, subjectively deter-

mined criteria of performance. Also, a basic structuring of the decision task and some degree of recurrent behavior is necessary for the continuing estimation of model parameters. In circumstances that do not satisfy these conditions, the adaptive system can work with a variety of other analysis modes, acting as part of a decision support system similar to that envisioned by Leavit, Alden, Erickson and Heaton (1974). For instance, long range planning may be best done using tree elicitation and structuring (Brown, Hoblitzell, Peterson and Ulvila, 1974; Nickerson and Feehrer, 1975), while completely formulated and specified problems benefit strongly from the rapidity of decisions rules or preprogrammed responses (Brown, et al, 1974). Adaptive programs combine readily with and complement these types of aids, so that a major protion of decision-making, from problem formulation to performance evaluation, can potentially be supported.

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Table 1. MEANS AND STANDARD DEVIATIONS FOR THE TWO GROUPS ON THE PERFORMANCE MEASURES

MEASURE		AIDING	CONTROL	TEST
NUMBER OF DECISION CYCLES	$\bar{X}$	43.0	37.5	$p<.05$ t test, 10 df
	SD	3.1	4.6	
POINTS	$\bar{X}$	290.0	224.3	$p<.05$ t test, 10 df
	SD	28.7	50.3	
PENALTIES	$\bar{X}$	63.7	77.8	
	SD	8.7	18.2	
COST OF SENSORS	$\bar{X}$	68.8	61.2	
	SD	8.7	18.2	
SCORE	$\bar{X}$	161.8	86.2	$p<.05$ t test, 10 df
	SD	40.2	64.9	
DEU	$\bar{X}$	1307.5	2642.2	$p<.05$ Fmax test, 5 df
	SD	772.2	2471.4	

Figure 1. ADAPTIVE DECISION AIDING CONCEPT

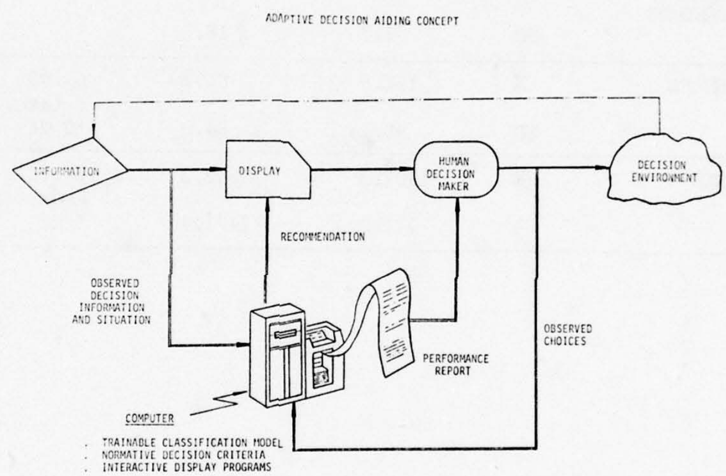


Figure 2

SCHEMATIC REPRESENTATION OF DYNAMIC UTILITY ESTIMATOR

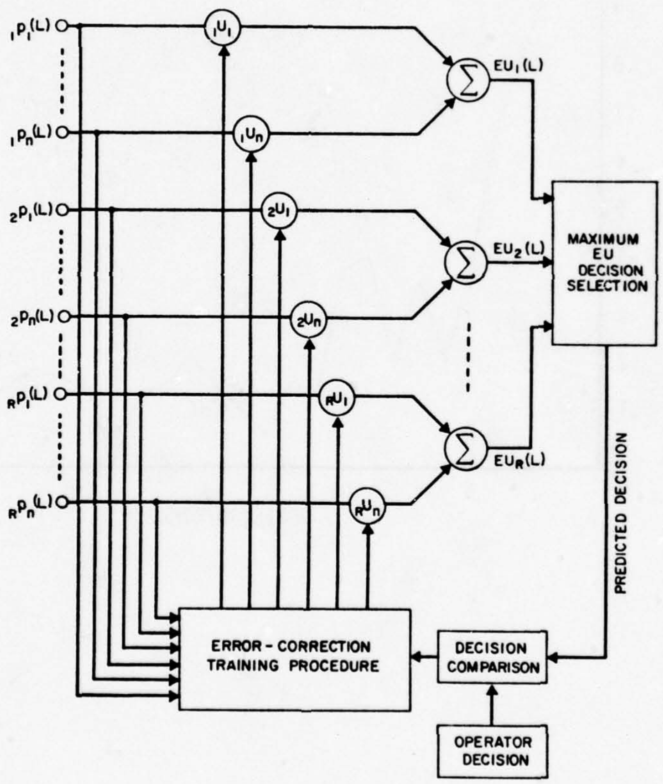
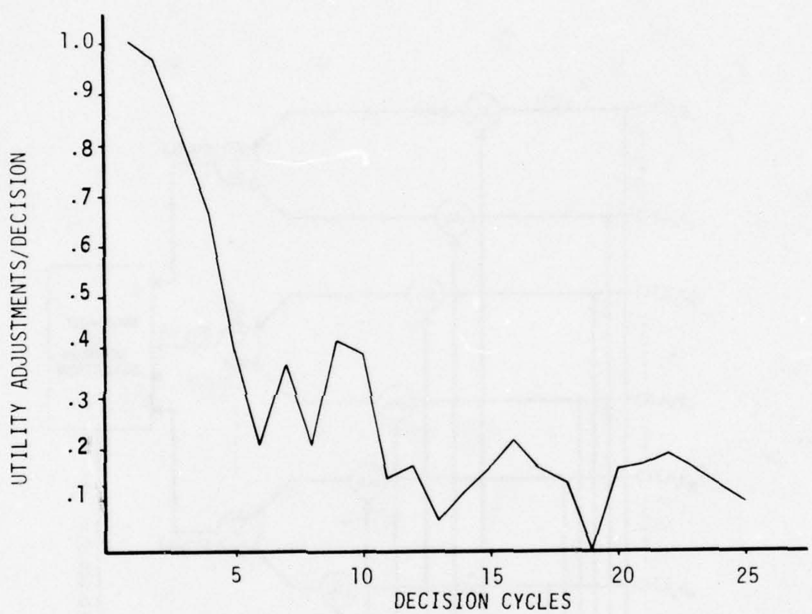


Figure 3

UTILITY ADJUSTMENT/DECISION FOR THE DECISION CYCLES ON WHICH THE TRAWLER SENSOR UTILITY WERE ADJUSTED (12 SUBJECTS)



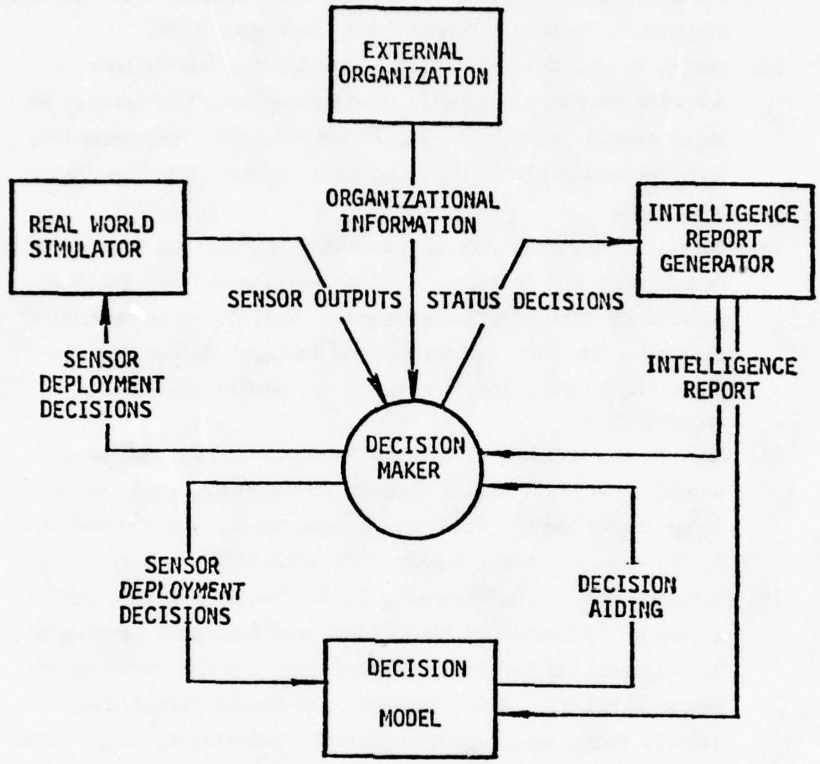


FIGURE 4. ADDAM SYSTEM STRUCTURE

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DISCUSSION

Lt. Col. Geesey: Can you give us some sort of feel for the state of understanding the theory for that kind of decision making process. It appears to be a linear type of structure. Perhaps the gentlemen here are more familiar with it than I am. But I would appreciate it if you would sort of comment on that state of theory with that sort of adaptive process.

Weltman: I wish I can, this is going to sound like my partner and I know everything in the world and that is one of the things he knows. I would be glad to send you our reports. Dr. Amos Freedy who sometimes gives the same presentation of results and couldn't make it to this meeting, is the one who deals with the theoretical aspects. It's not a put-off, but anything that I would say would be at such a low level that it wouldn't help you, but if you give me a card I will send you a paper that will explain some of the theoretical applications.

Geesey: The purpose of my question really was to point out the fact that the decision makers who work with this kind of system also have to understand this kind of structure.

Weltman: Well on the very simplest basis I would say yes. Let's go to the very simplest thing. We ran one experiment which was interesting. In one case we told the decision makers where the recommendation were coming from, that, in fact, they were coming from a process which was based on their own previous performance. In the other case we did not tell them, but we gave them the same recommendations. The ones who knew that they were their own preference used them and improved their performance significantly over the other group. So in that case you have, first even knowing that this was an adaptive process based on their utility was an aid to them. But you are right, there probably has to be some form of indoctrination. In fact we indoctrinate our subjects in some of the background of what it is they are seeing on the board. How deep that has to go depending on the personnel is something we

have to find out. But, because of this perhaps we have seen virtually no resistence in this. We are using subjects we are paying them so one doesn't expect it. On the other hand, they are not obligated to us. They don't work for us. They can tell us anything they want and they are fully representative of the type of people who use such systems. In fact, they enjoy it. I mean as I said, I wasn't being facetious about having a staff member. That for me coming at it from the technology side, I see computations as a staff member. I also see fun of ownership. I mean the same fun people get from discussing hot cars people get from discussing hot computers if they know something about it. To me it is a question of proper indoctrination and the use of it doesn't have to be frightening and can really be quite pleasant.

Bonder: Let me see if I understand what you are doing. This is not a model of decision making. You are not getting an adaptive model of the decision maker. You are adaptively learning about his utilities. There is an underlying assumation of a Bayesian decision maker. He is a Bayes decision maker. He acts out what is expected of him.

Weltman: *As I said, this is the basis on which we make our* initial prediction. If that prediction falls down, then we are in fact not modeling that decision maker whatsoever.

Bonder: If a man is not truly a Bayes decision maker these will not converge. Is that correct?

Weltman: If he is not acting in accord with his utilities. Remember somebody said this morning that a model is an abstraction. I am not going to stand up here and argue that people are in fact maximizing utility. In so far as we can predict the decisions in a situation which we can define, yes we have modelled decision makers.

Bonder: My question is: If that is true, then should we use it to train? If someone is not a Bayes decision maker, do you want to make him one?

Weltman: That is a political decision, but yes, if you do. I would say as opposed to irrational choices, yes I think I would. Somebody else might want to train them to be a different type of decision maker is what you are saying?

Bonder: No, no, I am just asking questions. I am trying to understand what you are saying - you are saying that I am only rational if I am a Bayes decision maker?

Weltman: No, I didn't say that. You asked that should we try to train them to be this type of decision maker. Yes, I see great value on certain circumstances. For example, in the maintenance work that we are doing, typical maintenance is not taught now as a judgment between risk and benefit. It's taught on other means. Now, by means of these types of models, we in fact teach them that a decision to make a trial measurement is a choice between the benefits of that measurement and the cost of that measurement. The fact that we use this particular model is helpful and is opportune. But, yes, in many situations I would say it is reasonable to train people to make choices on this type of a basis.

Bonder: The question is: Suppose I would use the model and instead of making him a Bayes decision maker, I would make him an aspiration level decision maker. I would only pick those actions that maximize some probability of an event occurring as opposed to maximizing expected return?

Weltman: That's why I said it was a political decision. You have to choose it on some basis. Whatever appeals to you and go ahead on that basis. I don't know if one has tested models in that same situation. You could certainly do that also and choose. Of course, what basis would you choose the models?

AN ARGUMENT FOR FORTIFIED DEFENSE IN WESTERN EUROPE*

by JAMES R. THOMPSON
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Having urged for the development of an applied mathematical approach for DOD problems which takes its axioms from military history, I give a simple example. Let there be two sides - the Blue and the Red - with strengths u and v. Consider the case where u and v are lumped scalar rather than vector quantities. Frequently, the model proposed for a combat between the two sides is Lanchester's first law.

$$\frac{du}{dt} = -c_1 v$$
$$\frac{dv}{dt} = -c_2 u \; . \qquad (1)$$

This system has the solution as functions of time and initial force strengths

$$u(u_o, v_o, t) = u_o \cosh \sqrt{c_1 c_2}\, t - v_o \sqrt{\frac{c_1}{c_2}} \sinh \sqrt{c_1 c_2}\, t \qquad (2)$$

$$v(u_o, v_o, t) = v_o \cosh \sqrt{c_1 c_2}\, t - u_o \sqrt{\frac{c_2}{c_1}} \sinh \sqrt{c_1 c_2}\, t \; .$$

A more common expression for the solution is

$$u^2 - u_o^2 = \frac{c_1}{c_2} (v^2 - v_o^2) \; , \qquad (3)$$

and u and v are considered to be at combat parity with each other if

$$u^2 = \frac{c_1}{c_2} v^2 \; . \qquad (4)$$

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Expression (4) has caused some concern among military strategists in their consideration of the outcome of a possible European war between NATO and the Warsaw Pact, for by (4) if u^* and v^* are parity strengths and the Red forces can actually achieve the level $v = kv^*$ (with $k > 1$) against a Blue force $u = u^*$, then somehow the Blue forces must achieve a new c_2' with $c_2' > kc_1^2$ if Blue is to win the conflict. In reality, the European situation would surely give the Warsaw Pact a value of v with $k > 1$, and NATO weapons technology would probably be hard pressed to obtain a weapons effectiveness k^2 times that of the Russians. Hence, the cause for concern.

An alternative strategy for Blue would be to lower c_1 to c_1' so that $c_2 > k^2 c_1'$. It is this approach which is advocated in this note.

Ever since the abysmal failure of the Maginot Line in 1940, it has more or less been taken as obvious that fixed defense is the strategy of failure. We would question this view. Historically fixed defenses have proved more effective as compact islands of resistance, rather than as wide dikes to hold back the enemy tide. The Maginot Line was clearly designed as a dike, as was the Great Wall of China, and both proved failures. It is perhaps unfortunate that the dike-like tactics of trench warfare had proved so effective in World War I. Otherwise, the French would undoubtedly have noted that they were basing their 1940 defense on an historically fragile strategy. Dikes generally can withstand force only from the front, as the Persians (finally) discovered at Thermopolae. If the dikes are sufficiently narrow and thick, however, they may be effective islands and very difficult to overwhelm. It was conceded by a number of the great panzer innovators - e.g., von Manstein - that Germany absolutely could not have taken the Sudetenland defenses in 1938.

The type of fortified defense advocated here is not that of the dike, but that of the archipelago of islands. There is a natural tendency to scoff at what appears to be an advocacy of the construction of "castles" in the Twentieth Century. In spite of the tendency of some to denounce every military precedent over twenty years old as obsolete, we give below a few historical examples of "castle" defense.

In the books of the Maccabees in the Old Testament, we have examples of Seleucid defenders of the castle in Jerusalem holding out against the Hebrews for whole years, after all Seleucid armies in Palestine had been defeated, until relieved by later expeditionary forces. Tyre is, of course, a natural island castle and when defended as such has proved almost impossible to take.

Among the crusading orders, the Templars and Hospitalers early discovered they could maintain an effective Christian presence in the Near East only by concentrating a large percentage of their forces in a number of strongly fortified castles. Most of the military disasters to the orders were the result of their frequent willingness to strip their castle defenses and join the crusader barons in massive land battles - as at Hattin. It is interesting to note that one of the crusader fortresses - Malta - never fell to the Muslims and was only taken (by treachery) by Napoleon in 1798. In the Second World War, the connection between the resistance of Malta and the destruction of Rommel's Afrika Corps is well remembered.

Among recent examples of defense efforts of the "castle" variety, the defense of Westerplatte in September, 1939, by a reinforced Polish weapons company against a German army with tanks plus artillery plus aircraft plus a battleship for a full week is notable. It would be instructive to compute the Lanchester coefficients for this particular engagement.

As an example of castle defense which was seriously proposed but never executed, we have the famous national redoubt plan

advocated by members of Hitler's staff. Had a number of well provisioned citadels, manned by a few divisions of Waffen SS, been placed in the Bavarian and Austrian Alps, it is interesting to conjecture how long they might have held out and at what cost to the Allies.

Still more recently, we have the example of "castle" defense by Vietnamese units positioned in strategic hamlets. Their function was to maintain a government presence - even if the hamlet should be overrun - until such time as reinforcements were brought in from outside. The number of hamlets which were transformed from de facto Viet Cong control to ARVIN control by this device was quite significant.

In the examples above, there seem to be some common points. Fist of all, fortified defense gives a ready means of increasing the ratio of the Lanchester coefficients in favor of the Blue side. One natural advantage to this type of defense is the fact that the defender can increase his Lanchester attrition coefficient against a potential agressor by a policy of construction over a period of years. This may be a more fruitful policy than placing all one's hopes on increasing ones Lanchester coefficient solely by the design of new weapons systems. Historically, of course, defense effectiveness has been increased more often by fortress design than by weapon innovation.

Secondly, fortified defense should rely on adequate stores of supplies located within the "fortress" perimeter. It should be assumed by the defenders that they will be completely surrounded by the enemy for long periods of time. (In their fortress at Magdeburg, the Teutonic Knights always kept at least 10 years provisions.)

Thirdly, fortified defense is a task best undertaken by well trained professionals with strong group loyalty.

Fourthly, fortified defense is most effective when there are allied armies or potential allied armies poised to strike the

enemy at some future time and place. The fortress and the mobile striking force complement each other in their functions. The function of the fortress is to punish, harass and divide the enemy and to maintain a presence in a particular area. In general, however, offensive activities must be left to the mobile forces. The deployment of enemy forces to take fortified positions will weaken their ability to withstand mobile offensive operations.

Let us now examine the preceding arguments in the context of the equations (1), where now we consider c_1' to be variable. We assume that by the skillful construction of "island" defenses the Blue side may obtain a relation of the form $c_1' = f(u,v)$ which is described graphically in Figure (1). We assume that $f(u,v)$ never exceeds c_1, the attrition constant corresponding to non-fortified combat.

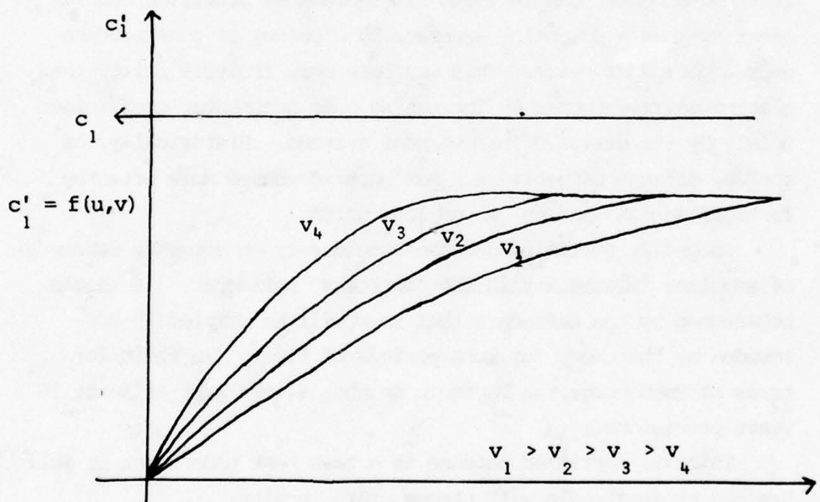

Figure 1

Clearly the function f and the value of the attrition constant c_2' are functions of the manner in which the fortress has been constructed. It may be desirable to design the fortress so that c_1' is small even at the expense of decreasing c_2'. Generally, one might assume that c_2' is close to the nonfortified attrition rate of u against v, since the defenders will have removed potential cover for the Red side. In fortress defense, the solution in (2), which involves time as a variable is likely to be important, since a primary objective is to maintain a presence for as long as possible.

Let us consider a reasonable first approximation to the v-level curves of f.

In Figure (2) we show linear segment approximations to f(·, v) for various values of v.

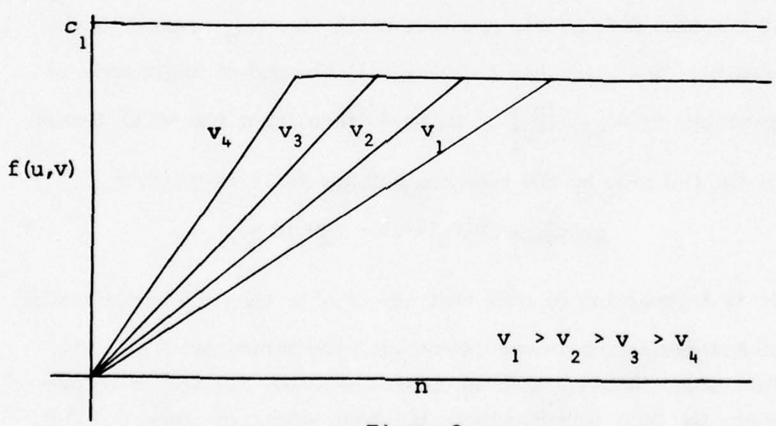

Figure 2

Here, in the u range (which is where we could expect most fortress defense to take place) we would have

$$\frac{du}{dt} = -g(v)uv - c_1^*u \tag{5}$$

where $f(u,v) = g(v)u$, and c_1^* is the Blue coefficient of internal attrition. We might reasonably expect that the besieging forces would maintain more or less a constant number of troops in the vicinity of the redoubt. Hence we would expect

$$\frac{dv}{dt} = -c_2'u - c_2^*v + P(u) = 0. \tag{6}$$

where $P(u)$ is the rate of replacement necessary to maintain constant u strength and c_2^* is the Red coefficient of internal attrition. We might expect that $c_2^* >> c_1^*$, since inadvertent self-inflicted casualties are a well known problem for the besieging force. Then

$$u = u_o \exp[-(g(v)u + c_1^*)t]. \tag{7}$$

The enemy attrition at time t is given by

$$\int_o^t P(u)d\tau = c_2^*tv + \frac{c_2'u_o}{g(v)v+c_1^*}\{1-\exp[-t(g(v)v + c_1^*)]\} \tag{8}$$

If the Blue defense can hold out until $u = \alpha u_o$ (where $0 < \alpha < 1$, possibly $\alpha = .1$), then the time till the end of resistance is given by $t^* = \frac{-\ln \alpha}{vg(v)+c_1^*}$. We have, then, that the total losses to the Red side by the time the defense falls is given by

$$\frac{1}{g(v)v+c_1^*}[c_2'u_o(1-\alpha) - c_2^*v \ln \alpha] . \tag{9}$$

It is interesting to note that if $c_2^* = 0$, then the minimization of Red casualties is consistent with the minimization of t^*. This might indicate that an optimum strategy for Red is to overwhelm the Blue fortifications by shear weight of numbers. This would not be true if beyond some value of v, $\frac{d}{dv}(g(v)v) \leq 0$, implying that beyond a certain strength, additional Red forces

would actually impair Red's ability to inflict casualties on the Blue side. As a matter of fact, the history of fortified defense seems to indicate that such a "beginning of negative returns" point in the v space does exist. Moreover, so far from being zero, it is generally the case for the besieging force that $c_2^* >> 0$. This is particularly true if the besieged forces are able from time to time to conduct carefully planned sorties in order to encourage increased confusion and trigger happiness on the part of the besiegers.

Under the same assumptions as given above we have in the case, where the Blue and Red forces have strengths $u = (u_1, u_2, \ldots, u_m)$ and $v = (v_1, v_2, \ldots, v_n)$:

$$\frac{du_j}{dt} = -\sum_{i=1}^{n} k_{ij}(v_i)v_i u_j - k_j^* u_j, \; j = 1,2,\ldots,m$$

$$\frac{dv_i}{dt} = -\sum_{j=1}^{m} \ell_{ji}u_j - \ell_i^* v_i + P_i(u) = 0, \; i = 1,2,\ldots,n. \tag{10}$$

This gives

$$u_j = u_j(0)\exp[-t(\sum_{i=1}^{n} k_{ij}(v_i + k_j^*)]. \tag{11}$$

The total attrition to the ith enemy subforce at time t is

$$\int_0^t P_i(u)d\tau = \sum_{j=1}^{m} \ell_{ji}u_i(0)\int_0^t \exp[-t(\sum_{j=1}^{n} k_{ij}(v_i)v_i + k_j^*)]d\tau + \ell_i^* t v_i \tag{12}$$

$$= \sum_{j=1}^{m} \frac{\ell_{ji}u_j(0)}{\Sigma k_{ij}(v_i)v_i + k_j^*}\{1-\exp[-t\Sigma k_{ij}(v_i)v_i]\} + \ell_i^* t v_i$$

Suppose that the effectiveness (at time t) of the defender is measured by

$$T(t) = \sum_{j=1}^{m} a_j u_j \; , \tag{13}$$

where the a_j are predetermined relative effectiveness constants. If we assume that the fortress is lost when the effectiveness is reduced to some fraction α of its initial value, i.e., when

$$T(t) < \alpha T(0) \ , \tag{14}$$

then we can use (11) to solve for the time of capture.

The above model has been designed to show how attrition might proceed during a fortified defense. Because of the rapid advance in technology over the past fifty years, military planners have tended to rely almost completely on weapons systems technology to increase combat effectiveness. We suggest that a certain amount of effort should be expended in an investigation of the older procedure for increasing effectiveness - namely, fortification.

This is particularly true when the United States is being opposed, as in Europe, by an aggressive power with great strength both in manpower and in weapons technology.

Of course, everything in defense planning must be done in the shadow of atomic weapons. It is true that fixed defenses could be destroyed by sufficiently large nuclear warheads - just as could any city or military base on earth. However, the use of nuclear weapons against military installations is well up the rungs of the escallation ladder. If the Soviets would be willing to use such devices in Europe, they would understand the order of magnitude of the risk they ran. One might use the argument, "Yes, we could construct hard defenses in Europe, but if the Russians found they could not take them except by nuclear weapons, they would use nuclear weapons." But this more or less presupposes a situation in which the Russians would take Europe, or else. In such a case, the United States has its own nuclear weapons.

NATO, however, is primarily designed to be effective for scenarios lower down the escallation ladder. At the present time, an invasion of Western Europe by the Warsaw Pact would quite likely force the United States either into a nuclear exchange or into a costly fighting retreat followed by negotiations leading

to the taking of some or all of Western Europe into the Soviet sphere. The establishment of a number of NATO redoubts would give NATO time to consider the situation and apply counter-pressures in an optimal fashion.

In conclusion, I am very much aware of the existence of defects in the above model. The mathematics are quite simple, going back at least to Kelvin's kinetic theory. The point is that the approach was motivated by historical data and that the model was not a warmed-over business case-study. If applied mathematics is to play any useful part in the development of strategy and tactics, then it is essential that our model-building approaches be developed in cooperation with the intuitive knowledge of career officers and in the light of military history.

COMMENTS ON PROPENSIONS IN MATHEMATICAL MODELLING

by THOMAS G. HALLAM
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In response to the invitation to participate in this systems group discussion, I claimed personal ignorance in the area of modelling tactical control and command. When the retort to this concern indicated a need for external participation, I accepted because my present interests, plankton models, are probably as "external" as one can get. The following philosophical comments should be evaluated from this exogeneous perspective.

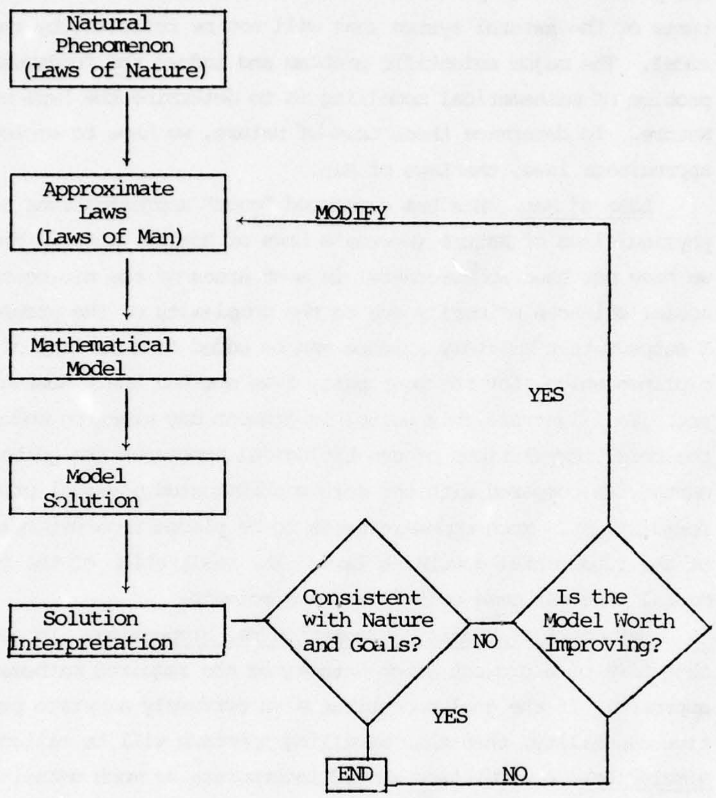
1.0 A Suggestion for Qualitative Studies. A modelling perspective which, in my opinion, has not been sufficiently emphasized at this workshop is the qualitative aspect. I shall make a few comments on mathematical modelling in general and the qualitative approach in particular.

Mathematical modelling by its nature is interdisciplinary... to be interdisciplinary one must first be disciplinary in two or more subjects. Major modelling problems can, and undoubtedly have arisen in a subject as complex as control and command primarily because there are apparently few experts sufficiently knowledgeable in the mechanics of C^2 and also sufficiently proficient in mathematics to handle the problems. The need for training such experts is great and several good suggestions along this line have been proposed by Professor Kalaba.

2.0 The Modelling Process. The flow chart in Figure 1 is a skeleton schematic representation of the modelling process. I shall now discuss some of the components in the diagram.

Figure 1

A Schematic Representation of the Modelling Process



Laws of Nature. No model of a phenomenon will be a correct model of that phenomenon. The model will exhibit characteristics not present in the phenomenon and, conversely, there will be features of the natural system that will not be reflected by the model. The major scientific problem and indeed the fundamental problem of mathematical modelling is to determine the Laws of Nature. To determine these Laws of Nature, we have to employ approximate laws, the Laws of Man.

Laws of Man. Man has developed "good" approximations to the physical laws of Nature (Newton's Laws of Motion, etc.). However, we have not been so successful in most areas of the biological and social sciences primarily due to the complexity of the problems. I suspect that military science can be added to this list of disciplines which, for the most part, have not had their Newton as yet. To illustrate this point, in present day plankton models, the model formulations of the biological processes are quite elementary as compared with the more sophisticated physical processes formulations. Much emphasis needs to be placed upon determination of the fundamental governing laws. The realization of the fundamental laws can come only from basic science.

Mathematical Models: Simulation vs. Propension. The goal or objective of a project often determines the required mathematical approach. If the goal necessitates an extremely accurate predictive capability, then this modelling approach will be called a simulation. A simulation should incorporate as much detail as possible into the mathematical model.

A complementary approach to simulation in mathematical modelling will be called propension. If the project goal is the determination and understanding of the natural tendencies, governing characteristics, or rudimentary developments of the system being modelled, then only "essential" detail need be included in the model. It is, of course, a major scientific task to ascertain what data, processes, and effects are essential.

This classification of models into the categories of propension and simulation is to some extent arbitrary. The amount of detail in simulations can vary greatly as can the degree of understanding required of propensions. However, I have found the classification is useful if for no other reason than to force the modeller to consider his objectives carefully before plunging headfirst into the maze of analysis.

Table 1 contains a comparative list of some aspects of formulation and analyzation of mathematical models and is presented to indicate some differentiations between the two modelling approaches.

TABLE 1

A COMPARISON OF ASPECTS OF PROPENSION AND SIMULATION

I. Propension	II. Simulation
1. Macroscopic	1. Microscopic
2. Qualitative	2. Quantitative
3. Understanding	3. Predicting
4. Theoretical	4. Practical
5. Basic	5. Applied

Basic and applied research have often been regarded as distinct entities not only by our educational system and sociological structures but by our research funding agencies as well. This effects a lack of interaction which has diminished our capacity to develop theory in close collaboration with experiment and observation. Items 1, 2 and 3 in Table 1 more directly address the issue of the two alternative approaches to modelling than do items 4 and 5. The propension approach seeks to determine the governing characteristics of a phenomenon and to understand the natural tendencies and macroscopic ideas involved. The tools of this approach tend to be qualitative ones. Mathematical formulations can be simpler than with simulations. A simulation goal is to represent a phenomenon sufficiently accurately so that future behavior can

can be predicted. This goal requires utilization of each microscopic parcel of relevant information. Simulations usually are complex; hence, the tools are often quantitative ones. Use of a computer in model solution does not by itself make the approach a simulation one.

The main advantage of a simulation is that a high degree of accuracy is obtained but only for the particular problem for which it is designed. Generalizations of simulations are difficult since much information is specific to the situation. On the other hand, propension consequences are general conclusions about a system which may extend to general settings more readily. A simulation of a battlefield situation must be very detailed with personal and general field specifics, such as topography and weather, included. Such a simulation would probably not be applicable to another battlefield situation without extensive or complete revision.

3.0 Conclusion. Military science is, in my opinion, grouped with many other sciences, at the development stage where it is still better to trust a field practioner than an area theoretician. As such propension approaches could well be the proper direction for present modelling investigations.

To illustrate the type of question which can be addressed from a propension prospective, consider the following simplistic combat model. Letting N_i, $i = 1, 2$, denote the strength of the ith force, then from Montroll [1] we suppose that

$$\frac{\partial N_1}{\partial t} = \text{div } D_1 \text{ grad } N_1 + \beta_1 N_1[\text{grad } U_1] - \alpha_1 N_2 - \lambda_1 N_1 N_2 + P_1(t, r)$$

$$\frac{\partial N_2}{\partial t} = \text{div } D_2 \text{ grad } N_2 + \beta_2 N_2[\text{grad } U_2] - \alpha_2 N_1 - \lambda_2 N_1 N_2 + P_2(t, r),$$

wherein D_i, β_i, U_i, α_i, λ_i are parameters. Military strategy is concerned with appropriate choices of the advective components β_i grad U_i and the reinforcement functions P_i. Qualitative questions such as: When do the physical processes dominate the

interaction effects? When reinforcements are concentrated in a region, what effect does this have on opposing force strength? Should be considered from a propension viewpoint. With our present degree of understanding, it is perhaps this general type of information that a field commander should have at his disposal.

REFERENCE

[1] Elliott M. Montroll (1968), Lectures on Nonlinear Rate Equations, Especially those with Quadratic Nonlinearities, Lectures in Theoretical Physics, A. O. Barut and W. E. Brittin (Ed.), Gordon and Breach, New York, 531-573.

SCIENCE APPLICATION IN C^3

by GEORGE E. KNAUSENBERGER
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1.0 Creation of a Database. The dominant role of electronics in C^3 is unquestioned. Accordingly the application of resources and talent in this area promises that the latest advances in electronic science and technology are at the disposition of the C^3 users. What is, however, not clear is whether these applications are optimal and how the needs in C^3 can and should guide the development of the electronics technology. Obviously an integration of insights is necessary, the electronics engineer needs to study C^3 requirements and the tactician has to have knowledge of electronics capabilities and promises.

The problems posed in this context are extremely complex and, in my opinion, present understanding of the processes and needs is not sufficient to fully and systematically apply scientific modeling and optimization techniques in the design of C^3 architectures and networks.

For the relatively simple case of the design of telephone networks the microstatistics have been observed and macro-behavior been determined; queueing models are based on measured user statistics. For a military network these statistics are different from those of the civilian net. For the military situation there is also a strong interaction between the information flow and the "action flow", information flow statistics differ and depend on type and state of "battle". Related studies had been made already in the 1950's by the firm Haller, Raymond and Brown for the U.S. Army in connection with the observation of maneuvers. Also the Moore School of the University of Pennsylvania had been involved. These studies already demonstrated the absolute necessity for comprehensive observations of real field situations and showed the

complexity of the measurement and evaluation tasks which arise from the variety and elusiveness of the cause and effect relations. However great the difficulties are in the description of the logical processes, the effort must be made, in order to produce reasonably efficient information networks and proper definition of the information-action and action-information transducers for various alternatives of action flows and in order to possibly predict these action flows.

While the services have now studied the problems, found workable solutions, established data bases and created specific organizations, more involvement of electronic and mathematical scientists in the full reality of the C^3 problems could probably still be profitable. This involvement should concentrate first of all on observation, on measurement of events and the clarification of processes. While the importance of computers, real time signal processing, jam resistant data links or real time targeting, is well recognized, the systems aspects of sorting, distribution, reaction, interaction, in short the properties of information and action flow and the transduction between them, remain subjects of curiosity.

It seems therefore necessary to relax into a time of learning. Observation and measurement should be prime, and be complete as possible, before conclusions about tools like models or response-and transfer functions can be attempted. Such learning must be broadbased and long term to be thorough.

As long as the scientist with integrated insight in electronics, mathematics and in tactical and strategic operational sciences and practices does not exist, proper teams should be formed which engage in the study of maneuvers, actual, simulated or conceived. Military maneuvers should be used e.g. to instrument for data collection, in order to provide a data base for later evolution of optimal C^3 networks. Only after broad event and data study, the tools of modern mathematical theory and of

electronic technology can be applied with maximum benefit.

2.0 Creation of an Organizational Base. There is in my opinion a further need, an organizational one. Historically the Chief of Staff for military operations played the dominant role for all planning, also of the technology base. Developments have however demonstrated the importance and need for a Chief of Staff for Technology, who initiates application and generation of relevant weapons and information systems. Today, it seems, organization considerations are in order concerning the interaction between these staffs, because proper interaction will save resources and time; besides, the trade off between strategy and technology needs special people which can play a role in both the operation and in the design of systems, and which have to be trained. Organizational initiatives in this direction are recommended.

DISCUSSION

Otto Wech: Are you addressing directly to the Commander as operator or are you envisioning that the Commander interacts with the system by his staff?

Denicoff: Either way. From what we know of decision makers of that level, they tend to operate differently. They tend to use their staff differently. Some of them make extensive use of specialists and some of them like to get into details themselves.

Let me make one comment here, again I think we are trying to build in maximum flexibility. I very often here dogmatic statements in your direction. Namely the dogmatism says the Commander will never sit down and be terminal - utter nonsense. I have seen flag officers working at terminals and even get excited about that type of interaction. I think ther will turn out to be as much variance as there are individuals. Some senior officers will always want to rely on staff members. Others will want to interact on their own. One premise I have is very time you have to use an intermediary - another person - there is some restriction, some inhibition. If we are going to have feed-back, and that if feed-back has to go through a second and third generation until it gets to its Commander, a hell of a lot is lost. So there may be a real gain in some instances of having direct interaction between various people and the data base. At least we want to provide that capability that can be used or ignored.

Wech: At what level of steps do you determine the ability of the system to self adjust? Do you have control over that? Or is it a hardware or software given feature that you just take?

Denicoff: I would say we have two interests. One is to look at a particular configuration as a constraint on the world. Namely what is the best that can be done given that constraint? The constraint might be a hardware of soft constraint in the form of a system that has been posed. We must ask again, what constraints have been imposed by that system? How can those constraints

be alieviated given the restriction of that system? That's one goal. The other, I think, is a more research oriented goal, to end up with the specifications for the kind of hardware and software that has to be developed to make all these desirable capabilities possible. So one is to live with those real world constraints. The other is to write a specification to alieviate those constraints. You have both objectives.

Question: It seems that this process has a tremendous appetite for numbers and underlying distribution. Will you say something about how you are going to obtain this?

Kelly: Well, actually I would argue that it doesn't have too big an appetite for numbers. The number of judgments required for the model I just described, I would think, would take an experienced intelligence officer ahead of time something on the average of two to three hours and certainly no more than that. I might add that recently I had an opportunity to work on the problem that evolved. We involved a variant on this model and we were able to get the necessary input in both the stage two and stage three in about two hours. That says nothing about the validity of the numbers. I am sure you will grant me that. I realize that lots of people recover in a shorter period of time. I tend to think that, based on the consistency checks we did and the fact that the model seemed to give pretty good results. It's important to note that the message doesn't reside in the numbers. They are all very fuzzy numbers and really what we are trying to do is find out if the decision rules that are reasonably invarient can be identified.

Sacerdoti: I have a slightly related question here; how sensitive is the consistencies of those numbers and underlying models to be used because we will be dealing with different pieces of the problem at a time.

Kelly: It is rather hard to answer that without getting very specific. Some models are not very sensitive at all and in others it makes a tremendous difference. For example, this little dia-

gram I put up there. You could vary the weight designed to the different criteria all over the place. In fact, you could drop any of the four value criteria that we need as applicable. It wouldn't make any difference. In other models, of course, that is certainly not the case. I am sure there must be some underlying generalities, rules of thumb, we could use to make judgments of that sort, but we have not been able to identify many of them at this time.

Bracken: In the model that you constructed, as I understand, it there are various actions available to Blue certain probabilities of just taking those actions or perhaps adopting a mixed strategy.

Kelly: The options that are available to them are simple. Those are available to them - you can't rightly say as to what likelihood he will choose one. The intent is given possibilities in respect to Red's actions as to which option we should in fact choose. Should Blue shoot or not shoot, given the uncertainty that the incoming aircraft is an enemy plane.

Bracken: Well, let me answer the question in another way. How would you generalize this model if you were looking at things in a game theoretical context, where Blue had available to him some actions he might take with certain possibilities and Red did the same.

Kelly: One way is simply to say that the likelihood that Red is going to do something would be conditioned upon what Blue chooses to do and you simply represent it in the form of a conditional possibility. You run it out until sufficient time elapses so that carrying it beyond that point simply has no effect on the choices you are faced with immediately. The simple little model that I described didn't have that kind of conditionality in it. Others certainly do. For example, the choice of whether or ont to use certain tactical nuclear options in Europe would certainly determine to an extent what the Warsaw Pact might do. The impact or likelihood that the Warsaw Pact would go one way or another. If you simply look at that situation, you would work with probabil-

ities that are directly conditional on your own choices.

Bracken: I think that probability approach here is called for, not game theory.

Kelly: That is absolutely right. As a decision theorist I would approach it that way not using game theory, although one might well approach it using game theory.

Bracken: Don't you think there is some inconsistencies?

Kelly: No, but I am certainly willing to be educated. I can't think of any inconsistencies - none comes to mind.

Bracken: Well, if it's a sequence of simultaneous moves, then you don't get an opportunity to observe while you are moving. If it is a sequence of moves where Blue moves, Red moves, Blue moves, then you get a chance to observe, but if they are moving simultaneously...

Kelly: There is a difference between what one actually sees unfolding in the world and how one constructs a decision diagram that would help you choose a coarse of action today. You can certainly construct a decision diagram today under the assumption that the moves will be simultaneous and not sequential. In that case, of course, the probability, at least in the first stage moves of Red, will not be conditional upon what we do.

Bracken: What do you do then?

Andrews: I guess you would make an estimate of the situation based on the intelligence you have available. It doesn't seem to be a very satisfactory answer, but it appears to be the only one available.

J. Thompson: If you are saying to use a diagram such as you have indicated as an Educational Aid, I think there are useful. But if, as I understand, you are actually proposing this to be a decision aid in real time, in real world situation, I find it absolutely terrible! That is a tactic Commander who is going to be sitting in Washington watching a stochastic bug walking across a triangle which has probabilities which are very fuzzy and utilities which are very fuzzy. It seems to me very dangerous.

Particularly since the CIA syndrome may tell him that as soon as the bug crosses the attack boundary, we should attack.

Kelly: I don't think it doesn't actually say that.

J. Thompson: Well, what does it say? It says the machine is telling you to attack and you do what you please.

Kelly: Well, that is not what it says. It says, based upon the inputs and under these conditions, you should, in fact, prepare to attack and execute. Now, just as the trigger that Bob was talking about earlier in respect to Daisy is designed to evoke some kind of response from the decision maker, to that extent, that is doing exactly the same thing. It is designed as an aid based upon the commander's perception of the situation with some of the data put in ahead of time and some put in in real time.

J. Thompson: Not basically though, I mean it is the decision part and therefore it is a bit more than just useful information. I think your example about what things have been tried in business works pretty well. It points out a key difference between a military situation and a business situation. That is, nations can't take the bankrupt law. If you try something based on such and such data and such and such a utility function in business and you are wrong, you just take the bankrupt law and wait six months and you start over again. Nations can't do that.

Kelly: Well, let me answer that in the following way. You said this terrified you, but there is something that ought to terrify you more and that's people trying to do all this in the head of a single individual.

J. Thompson: I am sorry, but I am willing to trust this to an experienced Commander. In certain situations he gets his information from the Secretary of State, maybe even the President. But you are really talking about a situation where Blue was the United States. This is an honest-to-God situation. You watch it in simulation. If I understand it correctly, the way you are talking about it in such a situation where Orange is the satel-

lite state of Red and Blue is the U.S. Here is the Commander watching the little bug walking around instead of getting on the communications system and getting all the information he can from his subordinates and also from his superiors. I think that terrifies me a good deal more than anyting that is in the head of one individual.

Kelly: Well, I think, of course, that is the complexity of some of these things we are going to be evaluating during the next year. I think that what I have presented is a tool. To the extent that it is used correctly, I believe it can be of use, and can be quite valuable. To the extent that you have someone who says, "Gosh, the bug crossed the threshold and therefore I am going to push the button." That's like saying a monkey wrench is no good because someone else can go out and hit someone on the head with it. I think it is most important to keep the context straight. What they are talking about is a sophisticated aid. A clever version of a Commander's oracle, so to speak. Nothing really different except the implementation from the underlying framework from the system used in the British Navy and employs today. I share your concern because one of the things that bothers me is that people won't use this correctly. I do know enough about unaided intuition to know that there are some good decision makers and some bad decision makers. I think that for those that aren't as facile as others something like this is probably a better alternative used in an aid than letting a chap muddle through on his own.

Welch: Let me understand what you are saying here. It seems to me that one way to describe what you have there is a way systematically to mix current data with another set of data with a set of value judgments, of a set of logic connections, which you though up prior to the event. For example, the logic tree and the different kinds of concern and the weight you put on those concerns. That, to me, seems to be considered data as well as anyting else including the mission you are given among other

things. It does seem to me one simple way to describe what you chose to talk about is at least a systematic way of mixing current data on situations and post data.

Kelly: That is absolutely correct and it might be thought of in another sense. As a way to intergrate both the J2 and the J3 while preserving their integrity.

Bonder: It is a bit more than that Jeff. It does suggest that if one were "rational" one would act per the action space partitioning.

Kelly: Right, I am assuming that you got all the risk and everything else in there that I didn't even talk about.

Bonder: There is an action space there that is divided and it is divided based on beliefs and certain assumptions made y a great mathematician a few years ago. The tree folding back is based on some logic that is some set of assumptions about how one folds back trees. One folds back trees that way if you believe the "assumption" on how to fold back trees. I am not saying they are right or wrong. I am just saying there are explicit rules on how to fold back trees. All I am saying is the Commander should know he has certain transitivity kinds of beliefs about the world before he should say, "I see that kind of space, I'll that way". You all know what I am talking about I think, in so far as what axioms I am refering to. If he believes in it, fine. If he doesn't, he ought to think about it a little stronger before he says something. It is more than just a data basis. It is a decision making logic that is considered to be rational if you believe in a certain set of axioms. All I am saying is a Commander should know what they are if he wishes to follow that kind of prescription.

George Pugh: I think the thing that bothers me most about the decision aid is the underlying assumption that your conditional probabilities are constant. I understand that the user puts the conditional probabilities in on the assumption of various scenarios that he thinks of as possible alternative enemy courses

of action. If a different set of scenarios begin to unfold, he might have wished he had put in different conditional probabilities. My question is: Do you have in mind some way of testing the probably constancies of the conditional probabilities in some sort of realistic situations?

Kelly: The intent, really, when we began this whole set of probabilities was to present the modified J2 as a situational on holding. So that is the negative in which we are supposing to accomodate. To answer your question; what we are doing now is looking at a variety of scenarios using the same framework and simply trying to get a feel for the extent in which these probabilities change, and what characteristic of scenario is responsible for the change. And this leads to all sorts of speculation on updating and interpolation methods one might go to later, but that's quite far in the future.

IV. CASE STUDIES

INTRODUCTION TO GENERAL SYSTEMS PANEL

by LT. COL. R.A. GEESEY

I am not a scheduled speaker, but I would like to take a minute to describe an anecdote about our preparation for this workshop. Before working in Air Force Studies and Analysis, I was a researcher in systems theory and systems analysis — I have some alliance with this particular panel of the workshop. My systems background led me to try thinking in a systems way about the general problem of decision information and tactical command and control — that is, I tried to draw up a network structure for the problem; and I think yesterday's demonstration made clear enough where that approach leads — Colonel Thompson's "worm chart" showed the complexity of the network topology.

It was about a year ago that I had a conversation with Lieutenant Colonel Walt Rabe of the Air Force Office of Scientific Research about ways that Studies and Analysis and his office could get together various research disciplines for command and control interests. We felt that mathematics, statistics, and the physical sciences — as well as behavioral sciences, philosophy and many of the other disciplines that are in fact represented here today — interact in useful ways for application to the general area of decision information for tactical command and control. Lieutenant Colonel Rabe and I roughed out a diagram of scientific disciplines, the subareas within them, and some of the theories involved in research interests. Our diagramming of interconnecting relations between disciplines and theories quickly began to resemble the complexity of Colonel

Thompson's "worm chart."

I think we learned that there is a duality between the problems and their solution! There are obviously communication problems in the flow of information within combat information systems and the command and control processes. The duality is the communication among disciplines and technical areas — the flow of ideas and data that we are attempting to enrich by this workshop.

We were pleased to see the excellent exchanges in the earlier sessions and expect that this General Systems Panel will be able to further broaden our communication about relevant research. The remarks to be made by our participants for this panel can lead discussions into several profitable areas — some diverse from exactly what is going on within systems theory itself.

"THE LESSONS LEARNED IN TRANSLATING REQUIREMENTS INTO CAPABILITIES: THE WWMCCS ARCHITECTURE"

by KENNETH A. HOMON
International Business Machines Corporation

This paper summarizes from an information flow perspective the lessons learned in translating requirements into capabilities (technological solutions which satisfy requirements to varying degrees) for the world wide military command and control system (WWMCCS) architecture project. The purpose of the project was to develop WWMCCS architectural alternatives for the mid 1980's from which the WWMCCS council, comprised of:

Deputy Secretary of Defense
Chiarman of the Joint Chiefs of Staff
Assistant Secretary of Defense for Intelligence
Director of Telecommunications, Command and Control
WWMCCS Architect

could select a single architecture and to develop a transition plan for the implementation of the architecture. The architectural plan was the final result of approximately two years of analysis of WWMCCS requirements, baseline programs, and technology available for the next decade. That analysis emphasized the primary mission of WWMCCS as defined in DOD directive 5100.30, namely, support of the national command authorities (NCA). To carry out that mission, the direct mission support activities of the unified and specific commands and their component commands, the defense agencies, and the military services were included.

The requirements were based on an analysis of representative crisis and conflict situations that might involve U.S. military resources during the next decade. For each situation, NCA response options were postulated. The response option analysis was then used as a basis for documenting the functional and

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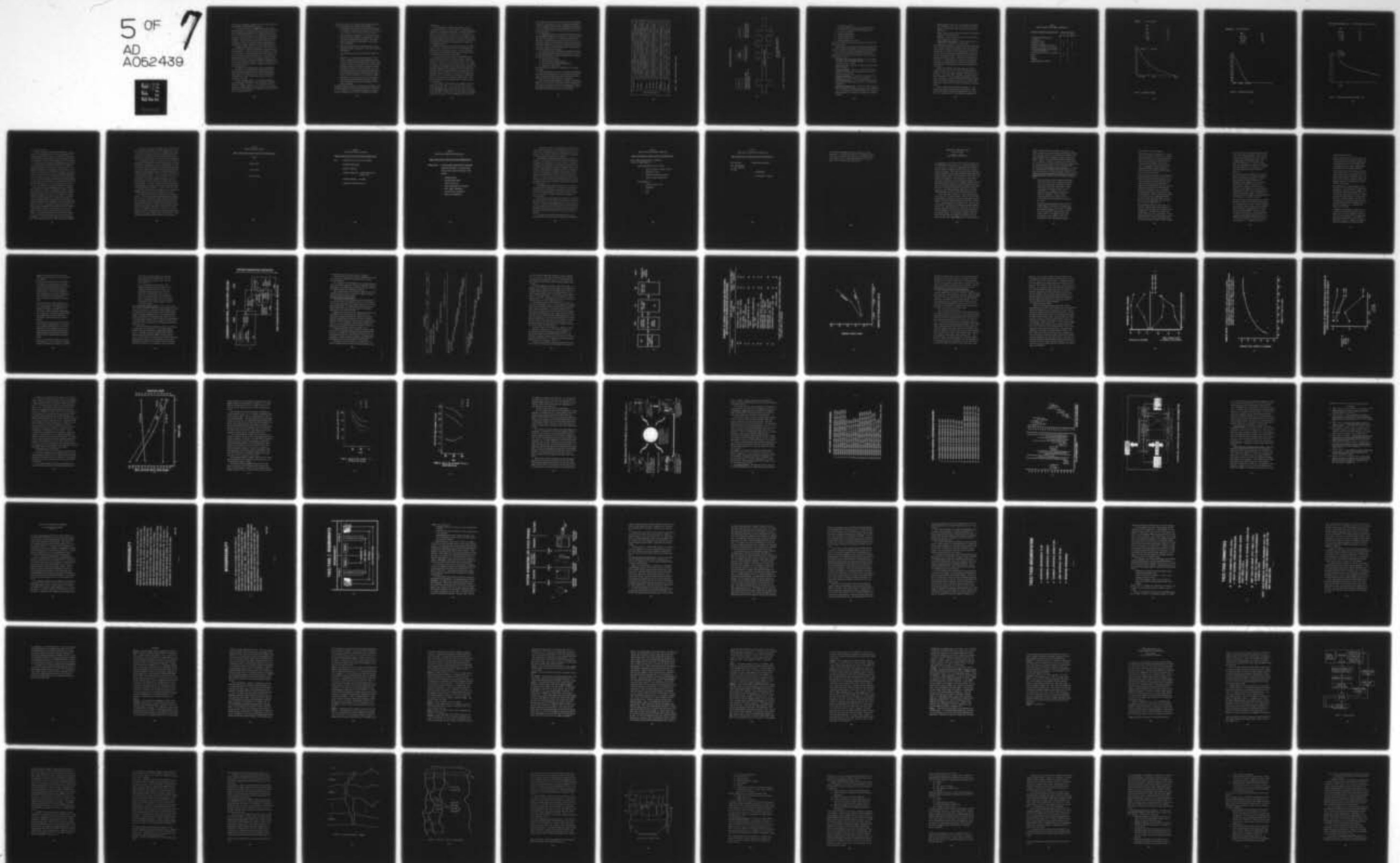

informational requirements, together with their associated performance parameters, which WWMCCS must support.

A concurrent analysis of the WWMCCS baseline (current programs) was conducted to determine whether the baseline capabilities met the documented requirements and to identify capability shortfalls. Each capability shortfall - for example, the lack of connectivity or the inability to counter the expected threat (physical, electronic, and nuclear effects) - was analyzed against available technology. Candidate feasible technical solutions were then developed and costed. The resulting capability improvements were reviewed with the WWMCCS community and with the WWMCCS council.

The WWMCCS council guided the architect in the selection of a set of high-priority capability improvements which they desired to be implemented (i.e., achieve full operational capability, or FOC) by the mid 1980's. These improvements, when incorporated with the baseline, comprise the selected architecture. Also included with the selected architecture are several major R&D programs; these programs are required to examine the technology, operational utility, and costs of several significant capability imporvements which could not be definitively evaluated, scheduled, and costed prior to such additional R&D.

The capability improvements which would be incorporated in the architecture, if the R&D programs are successful, together with capability improvements which the council decided were of lower priority, were identified as the long-range architecture. The capabilities in this architectural segment are planned to achieve FOC after 1985.

The two time-phased segments - the selected architecture, which incorporates the baseline, and the long-range architecture - comprise the WWMCCS architecture. The architecture is supplemented by a "corporate memory," which records all of the tentative decisions made by the WWMCCS council during their review and which led to the architectural plan.

The first major step in a C^2 architecture development process is to define the operational environment which includes:

- o The defense policy or policies under which operations will be conducted. A corollary of this factor is the national level objectives to which these policies are related.
- o The forces which are planned to be available for the conduct of operations, including the weaponry which will be available for employment by those forces. The current plans for modification and improvement of those forces must be understood.
- o The potential enemies against whom the forces are to be employed, together with estimates of their force structure and weaponry.
- o The national decision process within which C^3 must function.
- o The specific set of nodes and interfaces which C^3 must support. These nodes and interfaces represent a definition of the organizational boundaries of C^3 system. Major interfaces include the intelligence system, political and diplomatic systems, administration and logistics systems, environmental systems, and tactical systems. The input needs must be specified as interface requirements of the various architectures and a determination of the impact of those interface requirements on the interfacing systems.
- o Representative situations and options which translate the broad operational environmental factors into a useable form for requirements derivation and assignment of performance parameters.

We gained tremendous insights for developing the architecture from the analysis performed to determine the implication of each factor on C^3 requirements. Each was examined specifically to identify potential requirements and rationale for subsequent performance

requirements.

The requirements for a WWMCCS architecture in a crisis environment can be defined in two categories: information and capabilities or functional requirements. Information requirements define the flow, content and characteristics of information required for the performance of effective crisis management. Capability requirements define interfaces, procedures, communications and automated support capabilities that are required to facilitate the acquisition and exchange of information and to support the decision-making process.

Capabilities or functional requirements answer the question, "What must the C^3 system be able to do?" The requirements are driven by policy and planning guidance, factors of operational environment, and representative situations and options which partially formulate the operational environment.

In many respects the two categories of requirements are closely related with distinct similarities between individual requirement characteristics of the two categories. These similarities are indicative of the fact that the success of the WWMCCS is dependent upon the ability of the architecture to integrate the two categories of requirements into a common operational capability. The mutual dependency of the requirements is illustrated by the observation that the information elements identified will not be obtainable without the existence of relevant system capabilities. Similarly, there is no reason for the existence of system capabilities if no need for the information elements exists. When fully integrated, the two categories provide a complete requirements definition.

In the analysis of requirements for the WWMCCS crisis architecture for the mid 1980's, one of the major issues was how to ensure completeness. That is, how could one be sure that when a set of requirements had been identified, they would be sufficient to meet the needs of future crises? This was solved for the WWMCCS architecture in two ways. First, approximately 200 crisis situa-

tions involving the NCA over the past several years were examined to determine characteristics of crisis information requirements. Secondly, a highly structured analysis methodology was applied to a set of postulated crises which are representative of those likely to occur in the mid 1980's to quantify the full set of information requirements.

An independent analysis of the mid 1980's operational environment and expected alignments of nations set the range of values of the major factors involved in a C^2 architecture. These factors, which were called architectural drivers, are shown in Figure 1. A preliminary analysis of the two hundred crises revealed that they collectively spanned the set of major architectural factors shown in Figure 1 and that they possessed operational characteristics that would be common to future crises.

The structured analysis methodology for determining information requirements followed the general outline shown in Figure 2. For each situation/option, information requirements were analyzed to determine those necessary to:

1) characterize the situation
2) define the possible response options
3) select among the possible response options
4) implement the chosen option

The arrows depict the direction of information flow to support these tasks.

The detailed analysis of the set of 9 crises was performed by four teams of two individuals each. The experience and qualification of individuals assigned provided a broad cross-section of top-level military knowledge and analytical expertise.

After gaining an understanding of a situation, teams placed themselves in the position of addressing the tasks associated with each of the eight functional areas with the purpose of identifying the information required for effective crisis management. The functional areas pertaining to crises are listed below:

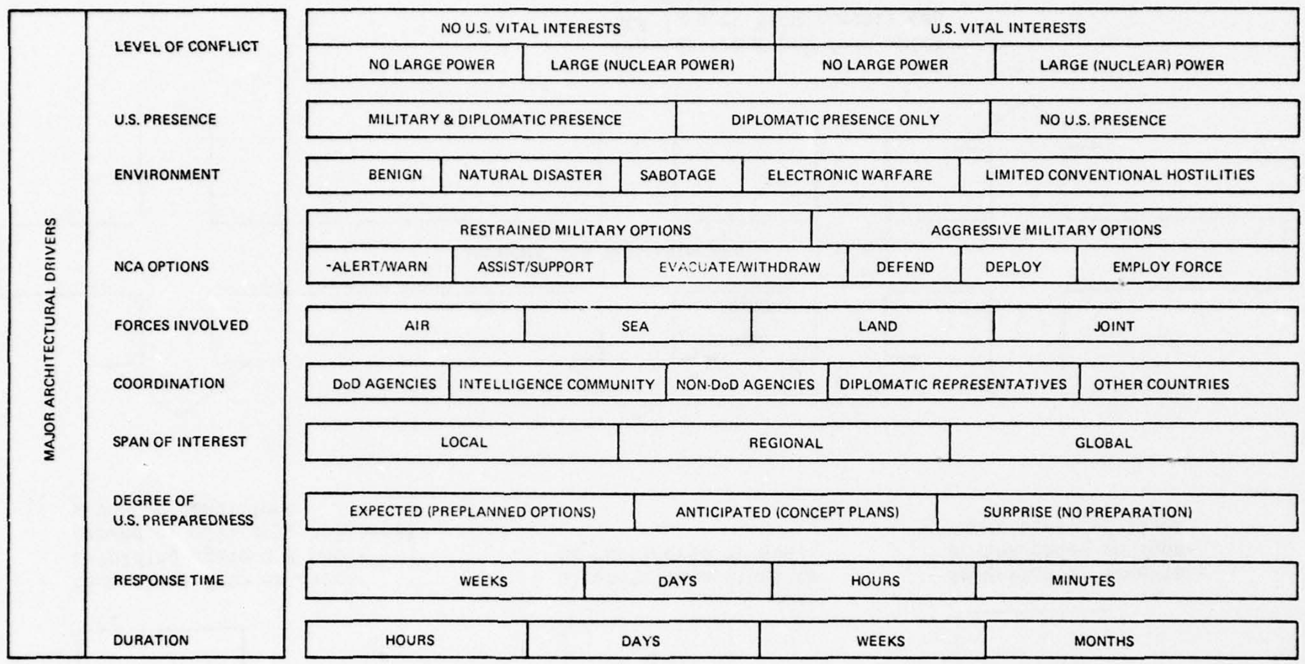

FIGURE 1. WWMCCS CRISIS MAJOR PERFORMANCE FACTORS

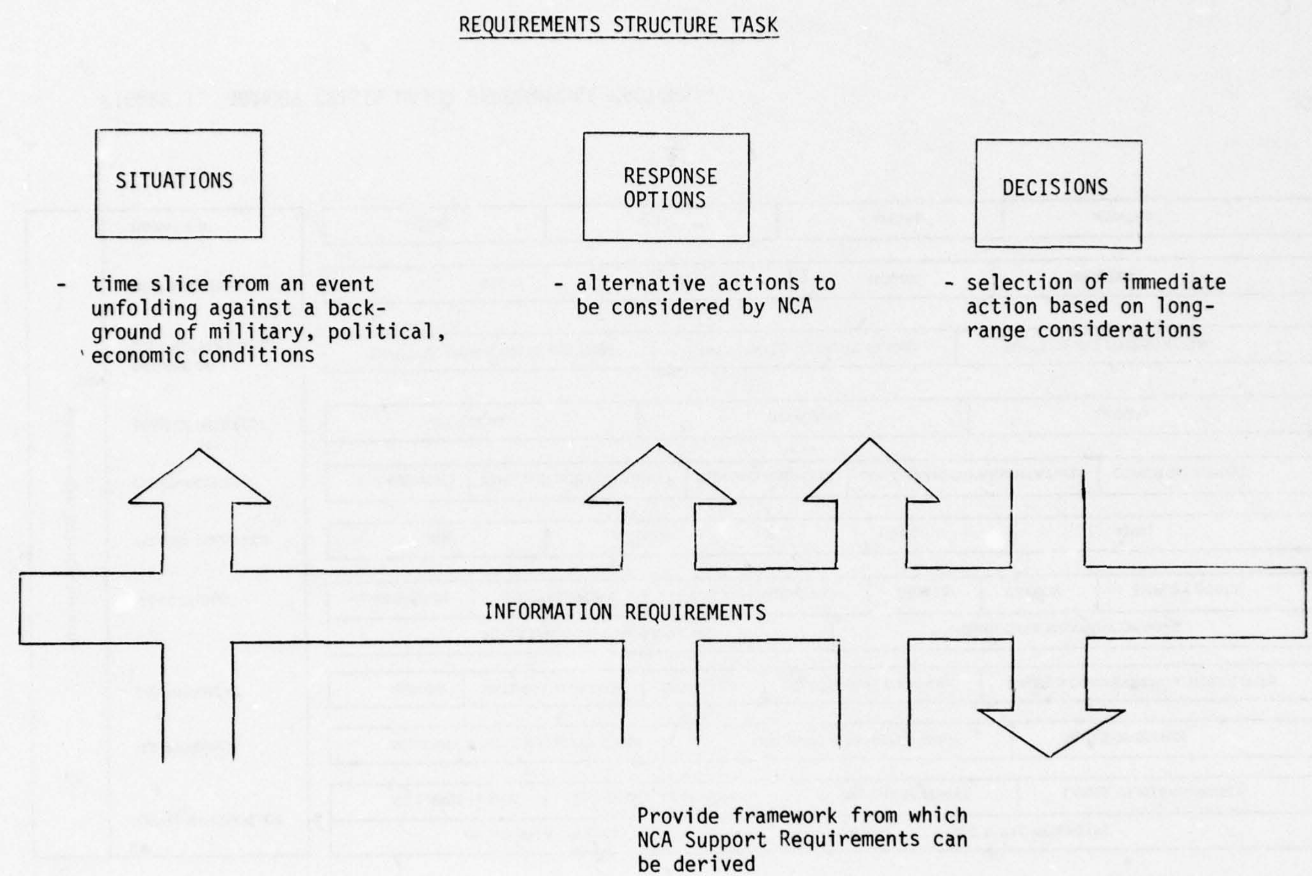

FIGURE 2. WWMCCS CRISIS REQUIREMENTS ANALYSIS

1. Indications monitoring
2. Potential enemy force and resource status monitoring
3. U.S./allied force and resource status monitoring
4. Planning and replanning
5. Warning and assessment
6. Selection and execution
7. Operations monitoring
8. Damage assessment and control

These functional areas collectively span the activity areas that make up each crisis.

Identification of information requirements was accomplished by each team through the development of key questions designed to uncover the critical information requirements for each situation.

For each question that was developed the analysts also developed a set of information characteristics that identified the following factors:

<u>Information requests/residence indicator</u> -- is the information supplied as an established procedure, or as the result of a direct query or request?

<u>Communication links</u> -- What are the sources and destinations of the information?

<u>Information currency</u> -- What is the maximum time gap that information should reflect with respect to the occurrence or condition being addressed?

<u>Information dependency</u> -- How dependent is effective crisis management on the availability of the information?

<u>Information precedence</u> -- How long should the physical communication of the information take, once it is available for transmission?

<u>Acquisition/development time</u> -- What is the maximum time that should be required to prepare the information for transmission if it is originated as a standard procedure? What is the maximum acquisition time available for a response to a request or query?

Mode of transfer -- What means of transmitting the information is most meaningful: e.g., data, charts and pictures?

Security -- What is the highest security level that must be associated?

Volume -- How much data in terms of words must be transmitted? (Applicable to data mode only)

Frequency -- How often during the crisis will this information transmission be required?

Formatted/narrative indicator -- Should the information be transmitted in a formatted or narrative form?

These information characteristics are shown in Figure 3 along with the architectural solution areas (WWMCCS element) most concerned with performance capabilities needed to satisfy the information requirements. We learned that each WWMCCS elements has to interpret the results of situation analysis differently because each was driven by different factors. Communications solutions, for example, were driven by threat: ADP was only indirectly driven by threat, i.e. through facilities. Therefore, the information requirements were supplemented by analysis of the operational environment which was documented as architectural guidelines for each element.

Examples of information requirements based on situation analysis are shown in Figures 4, 5 and 6 which represent three of the more critical areas. Figure 4 depicts the data currency requirements. This figure shows, for example, that data that is an hour old satisfied 70% of the information requirements for the 9 crisis situations, while data one minute old meets 100% of requirements. This figure also implies that there is a solution tradeoff between a highly responsive reporting capability and data base update.

Figure 5 depicts the data precedence requirements. This figure shows that data transmitted within 10 minutes of being available satisfies all precedence requirements for the 9 situations. The requirement for a rapid transmission capability is

FIGURE 3

WWMCCS INFORMATION REQUIREMENT CHARACTERISTICS

Information Requirement Characteristics	Architectural Element				
	ADP	I&W	Comm.	Exec. Aids	Fac.
Information Requested/Residence Indicator	X		X		
Communication Links	X	X	X	X	X
Information Currency	X	X	X	X	
Information Dependency (criticality)	X	X		X	
Information Precedence (transfer time)	X		X	X	
Acquisition/Development Time (requested/ original information)	X		X		
Mode of Transfer (voice, data, graphics)	X	X	X	X	
Security	X	X	X		X
Volume	X		X		
Frequency	X		X		
Formatted/Narrative Indicator	X		X	X	

CURRENCY: UP-TO-THE-MINUTE

TIME	%
1 MIN	100
1 HR	70
6 HRS	55
1 DAY	50
3 DAYS	20
1 WEEK	10

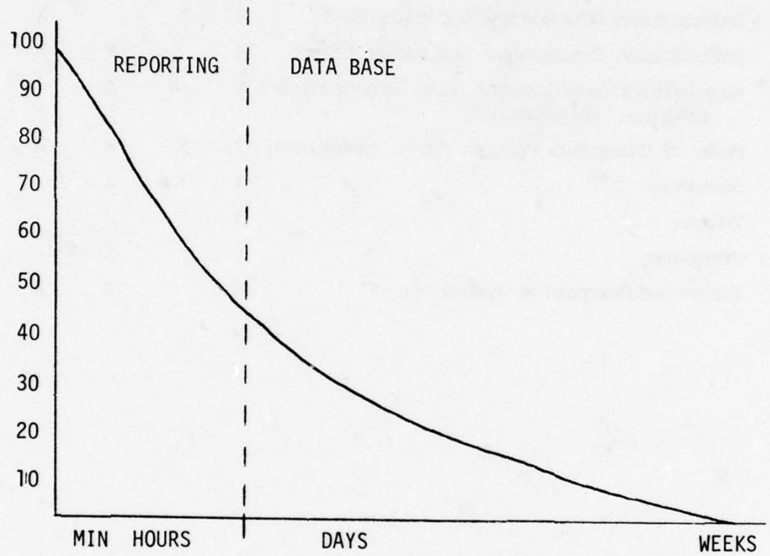

FIGURE 4. INFORMATION CURRENCY

PRECEDENCE: RAPID TRANSMISSION

TIME	%
≤10 MIN	100
10-60 MIN	80
1-6 HRS	35
NEXT DAY	5

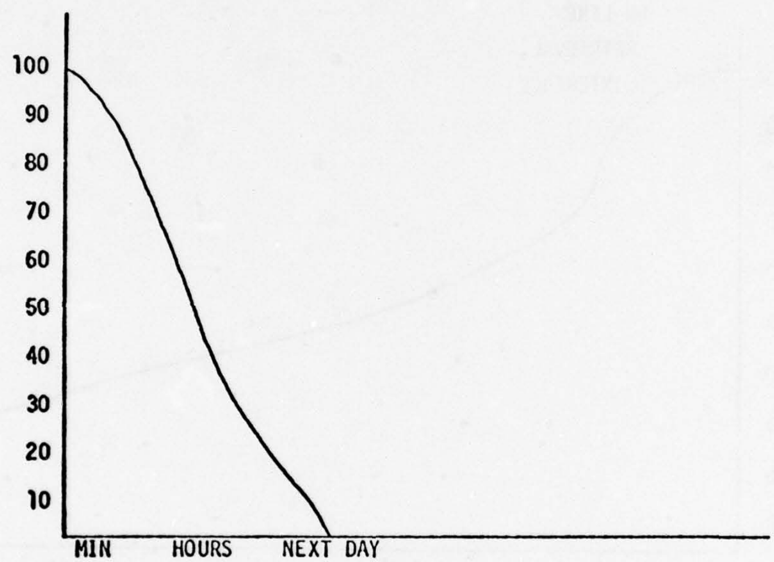

FIGURE 5. INFORMATION PRECEDENCE.

ACQUISITION/DEVELOPMENT TIME: RAPID INFORMATION EXCHANGE, RETRIEVAL

TIME	%
IMMEDIATE	100
≤ 5 MIN	95
≤ 1 HOUR	80
1-6 HOURS	50
1 DAY	30

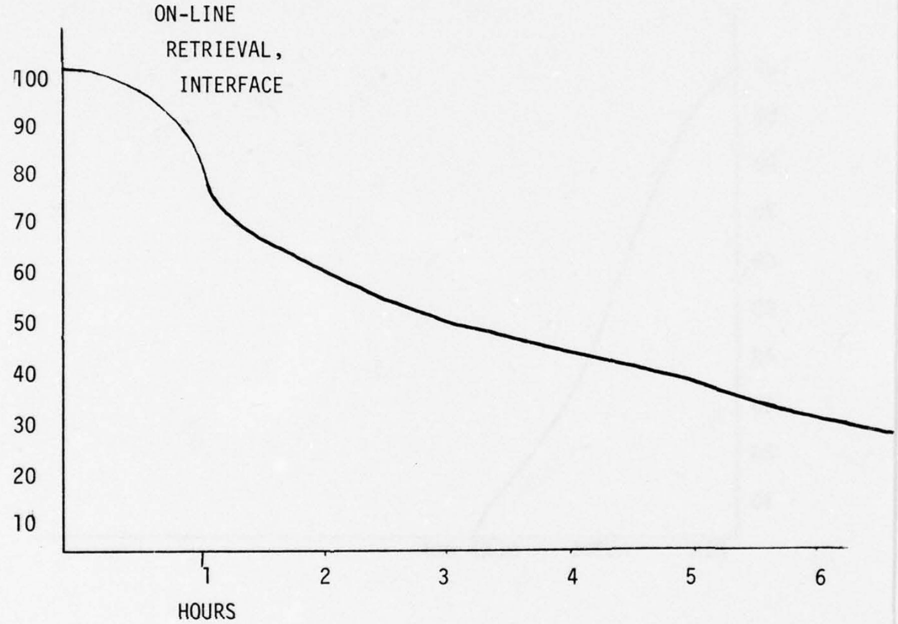

FIGURE 6. INFORMATION ACQUISITION/DEVELOPMENT TIME

obvious from this curve.

Figure 6 depicts data acquisition/development time requirements. This figure shows that 95% of the requirements of the 9 situations are satisfied if data is available for transmission within 5 minutes of being requested, and that data must be available immediately if 100% of the requirements are to be satisfied.

Traceability from functional requirements back to individual situation information requirements was maintained by numbering each key question and the answer to each question. Thus, if a performance capability is selected which satisfied 80% of the information requirements, it is possible to clearly state the situations in which the remaining 20% of the information requirements occur and see the effect of the selected performance capability. It was our experience that this traceability was much more important for the situation/options involving nuclear responses because of the architecture cost drivers. Since architectural costs did not vary significantly for crisis situation/options, this traceability is not needed for one crisis architecture over another.

While there is some interdependence shown in the examples just described, the total set of performance capability requirements was used and, indeed, provided sufficient data to develop architectural solutions for the five C^2 architectural elements. Performance parameters are unique to each element. For example, in ADP, the generic parameters are related to the volume and timeliness requirements for the categories of message processing, file update and maintenance, computation, query and response, and display activities. In contrast, the generic performance parameters required in communications related to the major categories of number and distribution of secure voice facilities, secure record facilities, secure voice conferencing, facsimile and imagery. This lesson was learned by initiating the development of a pilot architecture simultaneously with the definition of requirements. The pilot provided insight into what requirements are the most important and in what terms they are most meaningful.

The capabilities required to support the crisis total information flow can be focused at four generic nodes shown in Figure 7: The origin (the crisis location), the command center coordinating the crisis response, the decision maker responsible for taking action, and the CINC/force level responsible for implementing the military action at the direction of the decison maker.

The capabilities needed at the origin are shown in Figure 8. They include a transportable, hand-held reporting device with the capability of transmitting over a crisis alert network. In order that the data reported from the origin will be rapidly available to the users, reporting procedures are required that employ such features as standard message phrases, automatic formatting, and transmitting only parameter values for a pre-established list of critical information factors. All of this data can then be rapidly formatted at the receiving end and will also be in a form immediately processable by computers for dynamic handling and data base update. In order to maintain a current data base on involved assets in a crisis, the capability prescribes reporting events as required (as changes occur) by the origin rather than a prescribed reporting interval. To ensure an interaction capability between the origin and the command center an interrogation response capability for the reporting device is required.

The capabilities needed at the command center are shown in Figure 9. They include an automated message handling capability and the ability to automatically update data bases with message data and perform correlation assessments between reported data and data already resident in command center data bases. Additionally, there should be an on-line interaction capability among data bases maintained by operations, intelligence, and other agencies. The capability to maintain an action log to display current status and a chronological history of activities is also required so that anyone unfamiliar with on-going events or rotating shift personnel can review the entire log if necessary.

FIGURE 7

WWMCCS CRISIS GENERIC NODES

WWMCCS CAPABILITIES TO SUPPORT CRISIS TOTAL INFORMATION FLOW

ORIGIN

COMMAND CENTER

DECISION MAKER

CINC/FORCE LEVEL

FIGURE 8

WWMCCS CRISIS ORIGIN CAPABILITIES

WWMCCS CAPABILITIES TO SUPPORT CRISIS TOTAL INFORMATION FLOW

ORIGIN - REPORTING DEVICE AND CRISIS ALETT NETWORK

STANDARD MESSAGE PHRASES

AUTOMATIC FORMATTING

PARAMETER TRANSMISSION - MESSAGE CONSTRUCTION AT RECEIVER END

REPORTING FREQUENCY - AS REQUIRED

INTERROGATION RESPONSE CAPABILITY

FIGURE 9

WWMCCS CRISIS COMMAND CENTER CAPABILITIES

WWMCCS CAPABILITIES TO SUPPORT CRISIS TOTAL INFORMATION FLOW

COMMAND CENTER - AUTOMATED MESSAGE HANDLING/UPDATE INFORMATION CORRELATION ASSESSMENT -- (ON-LINE INTERACTION DATA BASE, INTER, INTRA-ECHELON, OTHER AGENCIES)

- o REPORTED/RESIDENT
- o OPS/INTELL/OTHER AGENCY
- o STATUS OF ACTION LOG
- o OPTION DEVELOPMENT/AD HOC PLANNING
- o GROUP DISPLAY CONFERENCING
- o ON-LINE DATA BASE INTERACTION
- o MODELS-COST CONSEQUENCES

In order for the staff at the command center to prepare the range of possible responses in a rapid manner, capabilities such as group display conferencing (where all participants see the same data), on-line data base interaction, and modeling or simulations to develop projected consequences are required.

The capabilities needed by the decision maker are shown in Figure 10. The decision maker must assess the different options available to him and decide on a course of action. In order to rapidly initiate a response, voice conferencing among all levels of command is required along with several different display capabilities. These include the capability to display force disposition, chronological events (including actions taken in related areas such as diplomatic and economic), and assessments of the situation by both operations and intelligence in an integrated display. In order to ensure that all participants have the same display data available to them, common background displays should be predefined and only the parameter or symbol values transmitted for display update.

In presenting options to the decision maker, the major factors which should be portrayed ar the length of time and the options which are still possible for execution, projected consequences of the option execution, risks involved, and anticipated cost, all of which can be updated dynamically throughout the crisis situation.

Once an option has been selected for execution, this decision must be transmitted to the CINC/force level selected to carry out the option. Key capabilities required at this level, as shown in Figure 11, include an acknowledgment feature which guarantees that the decision maker knows his instructions have been recieved, and simultaneous operations monitoring feedback to all higher levels that ensures they are fully aware of activities as the option is executed.

The top-down approach using situations and options and a characterization of the operational environment as the framework

FIGURE 10

WWMCCS CRISIS DECISION MAKER CAPABILITIES

WWMCCS CAPABILITIES TO SUPPORT CRISIS TOTAL INFORMATION FLOW

DECISION MAKER PRESENTATION/VOICE CONFERENCE -
(CINC, NAT'L TRANSPORTABLE C^3)

DYNAMIC SIMULTANEOUS SITUATION DISPLAY

- FORCE DISPOSITION -- (GRAPHIC, PHOTO)
- CHRONOLOGICAL EVENT
- ASSESSMENT (INTEGRATED OPS/INTELL)
- SYMBOL, PARAMETER TRANSMISSION

OPTION PRESENTATION

- EXECUTION, VIABILITY TIME
- CONSEQUENCES
- RISKS
- COST

FIGURE 11

WWMCCS CRISIS CINC/FORCE LEVEL CAPABILITIES

WWMCCS CAPABILITIES TO SUPPORT CRISIS TOTAL INFORMATION FLOW

CINC/FORCE LEVEL - COMMUNICATION OF DIRECTIVE

(CINC, TRANSPORTABLE C^3, UNIT, INDIVIDUAL PLATFORM)

- ACKNOWLEDGMENT
- OPS MONITORING - FEEDBACK

for developing the WWMCCS architecture proved to be a sound methodology. It allowed early insights into programmatic issues which could be brought to the attention of the decision makers and provided a level of detail commensurate with the decision makers' level of selecting among alternatives.

MAN-MACHINE C^3 SIMULATION STUDIES
IN THE AIR FORCE

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1. *Introduction*. Unlike many of the Air Force aeronautical weapon systems which have been based on a technology developed in the early 1900's, C^3 systems are comparatively new (since WW II) and have primarily blossomed in direct proportion to computer science technologies. Early human engineering efforts were addressed to aeronautical engineering problems, aircraft control and safety (altimeter studies), where the human operator (pilot) contributed significantly to system performance. Since safety of flight was so preeminent in early engineering endeavors for designing and testing aircraft, the man-machine compatibility problems were "roughly engineered" by aeronautical designers based upon their intuitive knowledge of human performance. Human engineering, as a discipline, developed, nurtured and thrived on making these "gut engineered" designs more efficient and safe through knowledge and data of man's performance capabilities.

On the other hand, C^3 systems, at least computerized versions, have only a 25-30 year history. Further, with the advent and development of computers to process the information in these systems, the functions performed became uniquely more "intellective", in an analogous sense, to human functions. Data are input to the computers (sensed), stored (memory), processed (problem solving), etc. This evolution of C^3 systems and the sister technology of computer science was prone to a greater propensity to be "gut engineered" or to "bright idea" engineering than even aeronautical systems. Also, operational personnel constantly strove for bigger and faster computers to minimize cycle and processing times without good evidence that the advantages to be

gained in system effectiveness warranted the expenses. The natural assumption is that more rapidly sensed and processed data can be used most effectively by operators and commanders in the field environment without taking into account the human's perceptual, intellective and information processing compatibility with the computer. Therefore, we find new C^3 systems insisting on 2.5 sec. cycle time of radar history without good evidence that this hardward/software capability can be effectively used.

2.0 Man-Computer Information Processing Capabilities. Following is a listing of human information processing capabilities and limitations published in a Honeywell document (12297-FR) entitled, Information Professing Framework for Man/Computer Interaction: A Research Study, which defines current state-of-the-art research issues.

- Man has extensive heuristic information-processing capabilities which cannot be duplicated by machine; he is able to apply creative solutions to unique problems and to eliminate large numbers of alternatives during the solution process (i.e., man is adaptable). The computer can be used to search and retrieve information based on man's direction and guidance. Due to its great speed of calculation, the computer can be an aid even when trial and error may be the only way to proceed.

- Man's problem-solving process appears to contain a random element which enables him to attempt solutions which may not be a direct result of standard rule-following procedures; he is able to innovate and, thus, may arrive at unpredictable but successful, results. The computer could be used as a partner in this "ideation" activity, by recording man's output and providing a medium

for generating novel relationships.

- Man requires a certain minimum amount of time in which to consolidate his thoughts (i.e., perform complex processing); this time is required primarily for the transfer of information between short- and long-term memory stores and for associating the information with the task at hand. A man/computer system organized on the principle of memory-to-memory communication should increase the efficiency of this consolidation and association process.

- Man uses definable strategies in his information-processing activities; these strategies vary in their rationality and effectiveness; man's strategies may reflect some basic cognitive style which is characteristic of an individual's approach to a problem regardless of task specifics; some strategies, however, are modificable by training or performance aids. In a computer-based system where such idiosyncracies form part of the data base, different cognitive styles would not necessarily limit or handicap performance. The less efficient strategies appear to place a greater strain on human memory, and this could be alleviated by computer-aiding.

- Man's performance appears to suffer when he is required to perform several tasks in parallel, especially when the tasks are in different stages of completion. The computer's capability for storage would be an asset in this regard, for the system could actually switch from tasks in various stages of solution as either relevant data were received by the system or human "insight" occurred.

- Man is limited in his sensory and cognitive ability to deal with incoming information, unless the pattern is regular and predictable; man has difficulty in dealing with multiple sensory inputs. This is an example where an interactive system could buffer the information (i.e., hold it in queue) until man could process the information. The system could thus compensate for the tendency of man to deal with information overload by selective attention.

- Man has a finite channel capacity which limits the amount of information in a stimulus configuration that he can deal with effectively; as task stimulus complexity increases, performance is degraded; relevant redundancy can help alleviate this difficulty; however, irrelevant task redundancy has a disproportionate interference factor. Given the appropriate guidelines, many of these types of problems could be eliminated by preprocessing the stimulus inputs. The effects of various levels of this approach on system performance and efficiency are not known at present.

- Man requires fairly complete information on his performance to maintain or increase his effectiveness; his own expectancies can exert a powerful influence when feedback is periodic during critical periods of skill acquisition; man progresses from a requirement for general knowledge of results to a need for specific task feedback. A system dedicated to interactive information processing could be programmed to adjust feedback requirements relative to the level of performance and his location in the task sequence (i.e., incorporate principles of

computer-aided instruction).

- The more deterministic the task environment, the simpler the task situation for man; however, man can effectively deal with complex probabilistic environments better than can a computer alone. The optimum approach to complex, unbounded problems appears to be man/computer synergism.
- Some relationships are more difficult for man to deal with than others (e.g., conjunctive problems versus problems based on disjunctive rules). In theory no such differences should be present when man is interacting with a computer to solve such problems, because the limitations due to human memory could be reduced.
- Most human beings are very susceptible to the influence of set or orientation generated by problem pattern, either structural or temporal; this rigidity can be evoked by relatively few occurrences of particular events; the effect is reduced by forgetting, thus suggesting the locus of the problem is in memory, probably short-term store. The capability of the computer to monitor behavior patterns would be useful in developing rules for alerting the operator (i.e., "breaking set"; another area for study).
- Man appears in many diagnostic situations to be a conservative information processor in that he does not use all of the information available in input data and accordingly tends to acquire more data than he either needs or can use prior to some terminal behavior. Computer aids have been proposed and implemented to reduce this human

propensity by allocating to a machine those tasks in which the man is more likely to display this tendency.

- Man's ability to formulate novel relationships is reflected in the fact that he is an effective information processor despite his cognitive limitations; this related to his ability to develop heuristics for information reduction and conservation. The role of the computer in this regard would be as a vehicle for depicting these relationships and for performing the analysis necessary for evaluation and verification.

- Man has been found to be more responsive to a criterion of accuracy than timeliness when both are system parameters. The computer has the capability to operate in non-real time (i.e., "fast time"), thereby providing the human operator the capability to evaluate many more alternative courses of action within limited time constraints without sacrificing his search for accuracy.

- Humans in decision situations tend to delay their action selection inappropriately; this is especially prevalent when the man is at a relative disadvantage. Again computer-aiding is a reasonable mechanism for channeling the operator's thought processes and overcoming this tendency toward inertia in problem solving and decision making.

- Man has a nearly limitless capacity for variety in his behavior; this is reflected in his unique capacity for innovation, originality, and creati-

vity; man has a special capability in the idea-generation aspect of problem solving. The computer can enhance this process, but it can by no means duplicate it.

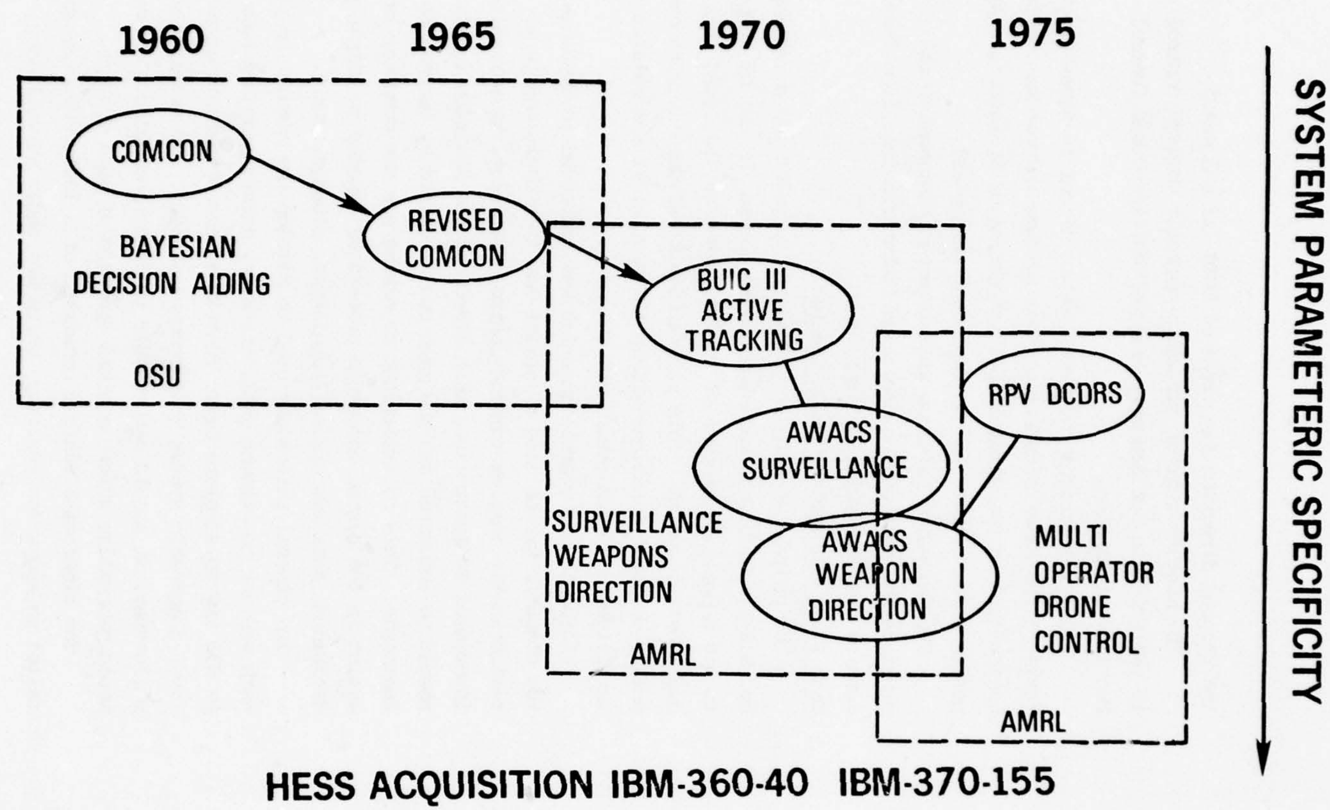
- Man is acknowledged to be a superior pattern recognizer especially when the patterns are both temporal and figural in content. Further, the interpretation of patterns, such as voice communication, relies upon man's ability to contribute his own experiences to the interpretation. Thus, for the present, man's role in this regard cannot be duplicated by machine but can be enhanced by providing variable displays capable of controlling pattern changes

3.0 C^3 MAN-MACHINE SYSTEMS EXPERIMENTS. Fig 1 shows a fifteen year history of Man-Machine Command and Control Simulation starting in the early sixties with a program in Tactical Command and Control decision aiding carried out under contract with Ohio State University's Human Performance Center. This program was dubbed COMCON (a simulated threat diagnosis system) and involved in an early version which had little feedback loops in the system whereas the revised COMCON included an action sequence and feedback load in addition to threat evaluation per se and operated on a greatly reduced time base.

When the OSU program was terminated in 1968, it was decided to develop an in-house capability in the Aerospace Medical Research Laboratory for Man-Machine Command-Control Systems Research. The Human Engineering Systems Simulator (HESS) was acquired involving an IBM 360-40 computer graphics facility. Since in the OSU program we investigated the man-machine diagnostic system behavior with very limiting assumptions of the sensor/surveillance environment, it was decided to direct our systems simulations activities to the surveillance, and to some extent,

FIG 1

COMMAND/CONTROL SIMULATION HISTORY



the weapons direction functions of BUIC III and AWACS.

The most advanced of our multi-operator command-control system is reflected in our Remotely Piloted Vehicle--Drone Control Facility Simulation.

Fig 2 illustrates the developments of our in-house program in terms of the major simulations, the systems independent variables manipulated in the simultations and the major operator and system performance measures taken (dependent variables).

The following sections will attempt to summarize the research problems and some of the more significant findings from these complex system simulation experiments.

Ohio State University COMCON Studies

The program at Ohio State University under the direction of Dr. William C. Howell was designed to assess the use of computers to aid a decision process of the kind that may be found in a command-control system. This program dealt exclusively with diagnostic decision functions within the context of a simulated intelligence threat evaluation system.

Although the overall question was addressed to determining if the computer can be used to assist man made decisions in a realistically complex command-control situation, we were also interested in determining what aspect of the decision function should be automated and how much can be gained by automating these functions. This is tantamount to asking how the computer can assist in the system inference process as opposed to simple predecisional data processing (tabulation, storage, etc.).

The general philosophy used to develop the simulation framework was not to attempt duplicating any existing system however, we did try to simulate basic functional characteristic of a high level diagnostic system (air reconnaissance). By adopting such a philosophy, it should be possible to determine principles which would generalize across a broad spectrum of such systems.

The simulation vehicle consisted of a 1000x1000 mile area called an aggressor territory which was under surveillance. Simu-

C^3 SIMULATION

FY70 FY71 FY72 FY73 FY74 FY75 FY76

BUIC/AWACS SINGLE OPERATOR STUDIES

MULTIOPERATOR AWACS SURVEILL.

WEAPONS DIRECTION

MULTI OPERATOR AWACS SURVEILL.

RPV DRONE CONTROL →

RADAR TRAIL-HISOTRY

RADAR CLUTTER

THREAT LOAD

BLIP/SCAN

PENETRATOR TACTICS

TRACK FAILURE RATE

CREW SIZE

SORKLOAD DISTRIBUTION

NO. OF RPVS

RPV GUIDANCE SYSTEMS

FORCE MIXING

PROB OF TARGET DETECTION

TRACK INITIATION TIME

TRACK MAINTENANCE

"OVERALL GOOD TRACKING"

PERCENT"KILLS"

DISTRANCE FROM BRL AT KILL

FUEL USAGE

CROSS TRACK ERROR

GROUND SPEED ERROR

PATCHES AND VELOCITY CHANGES

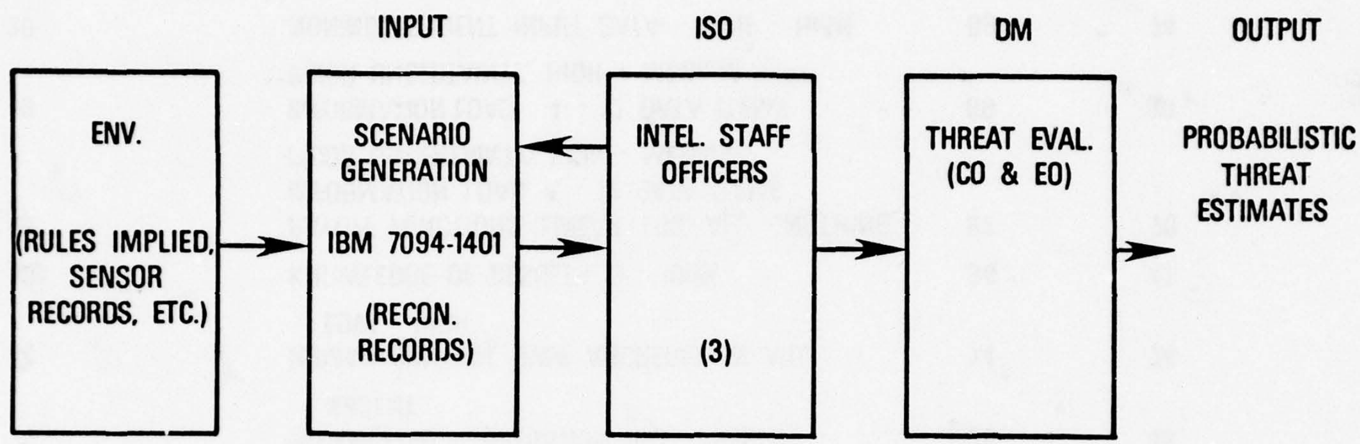
lated activities included troop movements, vehicular movements, etc., in this area. The input to the system was the processed reconnaissance data about these activities. These reports were then analyzed by the system in order to diagnose pending threat of attack.

The block diagram of the system is depicted in Figure 3. In general, the three Intelligence Staff Officers (ISO) attempted to determine what was present in the environment based on the reconnaissance data and report this to the Commanding Officer (CO). The CO evaluated these reports to determine what the data meant in terms of the aggressor's plans, e.g., training maneuver?, diversionary action?, etc. The system output was a set of probability estimates that each of these hypotheses was true.

The diagnostic process can be conceived of as actually consisting of two processes: first, is some estimation of the bearing that each bit of diagnostic data has upon the states of possible threat (evaluation process). It has been assumed that man is best suited to perform the evaluation function while the computer should perform the aggregation. By so doing man's special intuitive skills can be used for individual datum evaluation while the machine's capability for rapid calculation and memory can be used best for combining data to yield an overall diagnosis. To accomplish this latter function the machine must be provided a rule for determining how the information should be combined. The rule used in this program was Bayes Theorem.

The overall results of this program are summarized in Table 1. In general an improvement of 13% in correct diagnoses is achieved with automated over complete manual estimation. The greatest advantages of computer-aided solutions seem to occur when there is degraded input data due to low fidelity of sensors or stressful situations due to the information load generated by the amount of data to be processed. (See Fig 4)

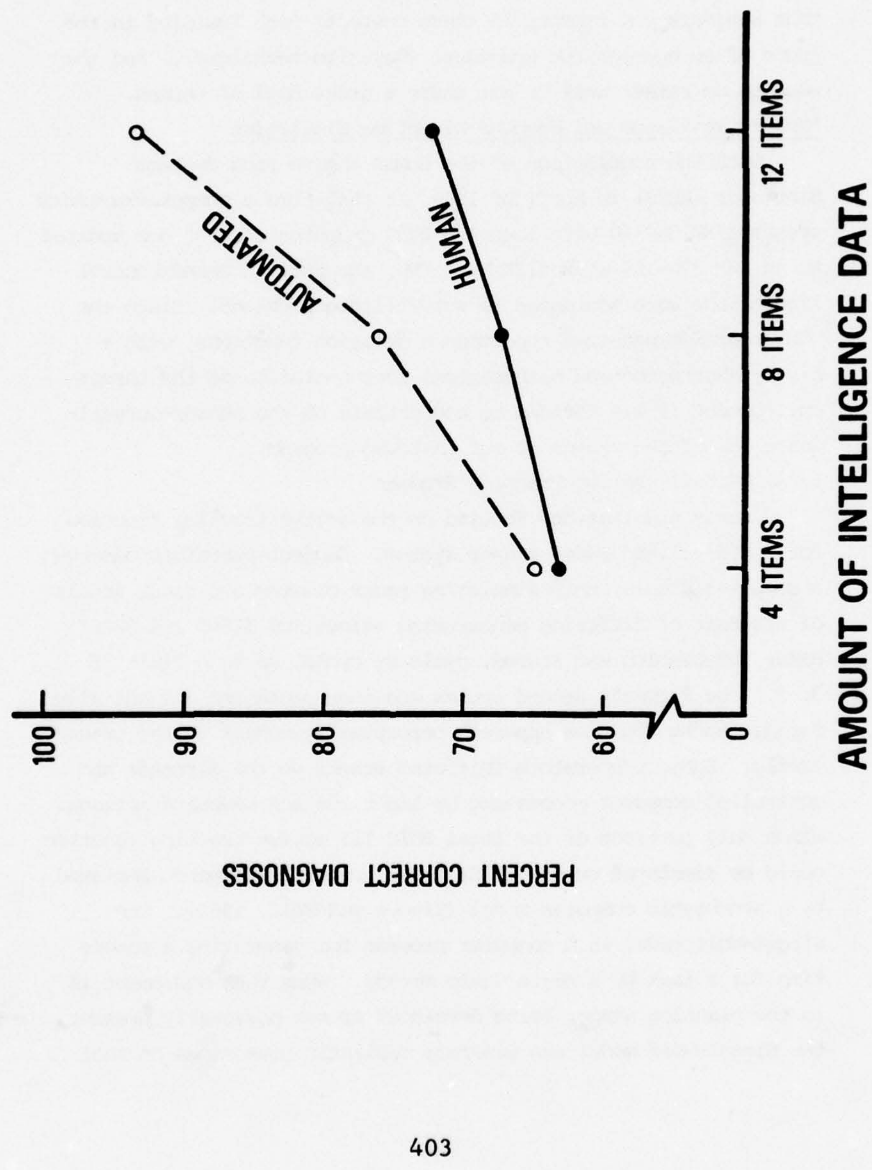
One reason that the computer aids the man under these situations is that it considers all of the information no matter how


INPUT
ISO
DM
OUTPUT
ENV.
(RULES IMPLIED, SENSOR RECORDS, ETC.)
SCENARIO GENERATION
IBM 7094-1401
(RECON. RECORDS)
INTEL. STAFF OFFICERS
(3)
THREAT EVAL. (CO & EO)
PROBABILISTIC THREAT ESTIMATES

SUMMARY OF OVERALL COMPARISONS BETWEEN HUMAN AND AUTOMATED AGGREGATION EFFECTIVENESS

EXPERIMENT	RANGE OF CONDITIONS STUDIED	AVERAGE DECISION SCORES* HUMAN	AUTOMATED
12A	EXPERIENCE: 114 HOURS -- 234 HOURS	47	54
12B	FIDELITY (INPUT): COMPLETE - MEDIUM	56	55
13	FIDELITY: MEDIUM - LOW TIME STRESS: 1 -7 MIN./DECISION	21	31
15	AUTOMATED AGGREGATION AID: PRESENT - ABSENT	25	45
14	HUMAN CONTROL OVER AGGREGATION AID: LOW - HIGH	74	74
16	KNOWLEDGE OF RESULTS: 0 - 100%	34	41
18	PAYOFF FUNCTIONS: LINEAR, LOG, ALL - NOTHING INFORMATION LOAD: 4 - 12 DATA ITEMS PRIOR UNCERTAINTY: HIGH - MEDIUM	62	70
19	INFORMATION LOAD: 4 - 12 DATA ITEMS PRIOR UNCERTAINTY: HIGH - MEDIUM	69	80
20	NONINDEPENDENT INPUT DATA: NONE - HIGH	69	74
	OVERALL AVERAGES:	45	58

* IN MOST CASES, THE SCORE REFERS TO PERCENT CORRECT DECISIONS AVERAGED OVER THE ENTIRE RANGE OF CONDITIONS.



AUTOMATED
HUMAN
100
90
80
70
60
0
4 ITEMS
8 ITEMS
12 ITEMS
PERCENT CORRECT DIAGNOSES
AMOUNT OF INTELLIGENCE DATA

degraded whereas man tends to ignore all but the highest quality information. Another reason seems to be that man is more conservative than the data actually justify. It appears, however, that subjects can improve in these respects with training in the logic of an aggregation procedure (Bayesian technique). And they seem to do rather well if not under a great deal of stress.

AMRL Surveillance and Weapons Direction Simulation

With the acquisition of the Human Engineering Systems Simulator (HESS) in April of 1969, at that time a computer graphics system (IBM 360-40 with four IBM 2250 graphics scopes) now updated to an IBM 370-155 with 512K byte CPU, the early command/control simulations were addressed to surveillance problems. Since the OSU program emphasized the command decision functions, with a highly abstracted and mathematical representation of the threat environment it was decided to concentrate on the sensor-surveillance end of the system of our in-house program.

·BUIC III Active Tracking Studies

Early simultations focused on the active tracking function for a digitalized radar sensor system. Subject-operators observed a computer display unit simulating radar clutter and radar trails of aircraft of differing penetrating velocities (150K and 500K). Radar information was stored, cycle by cycle, up to a limit of 3, 5, 7 or 9 twenty second cycles and then presented sequentially rapidly enough to give apparent perceptual movement in the track/trails. Subject/operators initiated tracks on the aircraft and controlled computer processing by light pen and keyboard actions. Since only portions of the total BUIC III active tracking function could be simulated on the HESS, other actual tasks were simulated by a stochastic computer model (Siegel and Wolf, 1963). The Siegel-Wolf model is a computer program for generating a sample time for a task by a Monte Carlo method. When task equipment is in the planning stage, being developed or not physically present, the Siegel-Wolf model can generate realistic task times on that

equipment. Fig 5 shows the findings of this simulation. Note that probability to detect was less and average time to initiate tracks was longer for the slower aircraft. It appeared that there was little advantage to have more than seven returns per trail in the track, both in terms of times to initiate and probability of detection. Two significant points seem to derive from this effort; first, using both computer simulation of tasks which could not be physically simulated in sequential combination with physical real-time simulation that significant sensor system effects on operator performance could be demonstrated and secondly, such a simulation approach can provide the trade-off data for deciding how much computer processing/storage is required to optimize operator surveillance detection performance.

AWACS Surveillance Studies

Early in 1970 the Airborne Warning and Control System (AWACS) System Project Office (SPO) requested that AMRL investigate surveillance operators ability to detect and initiate tracks on targets with varying degrees of ground and sea clutter. A series of simulation studies was initiated to investigate various sensor and radar filtering design issues. Fig 6 shows some early results from these studies on an operator's probability of correct track initiation as a function of the number of tracks he had to maintain throughout a fifty minute mission. It can be seen that under varying clutter density levels and varying target introduction rates into a 75x75 nautical mile surveillance zone that the more targets the operator had to maintain track on, the greater the probability of initiating new targets entering the zone. Also Fig 7 shows some results of these same studies. Probability of correct initiation of penetrator targets is plotted as a function of target introduction rate and clutter density. Note that in the worst case condition, when penetrators are entering the surveillance zone at four per minute and clutter density is fairly high, that one out of ten of enemy attackers will penetrate our surveillance zone undetected.

FIG 5

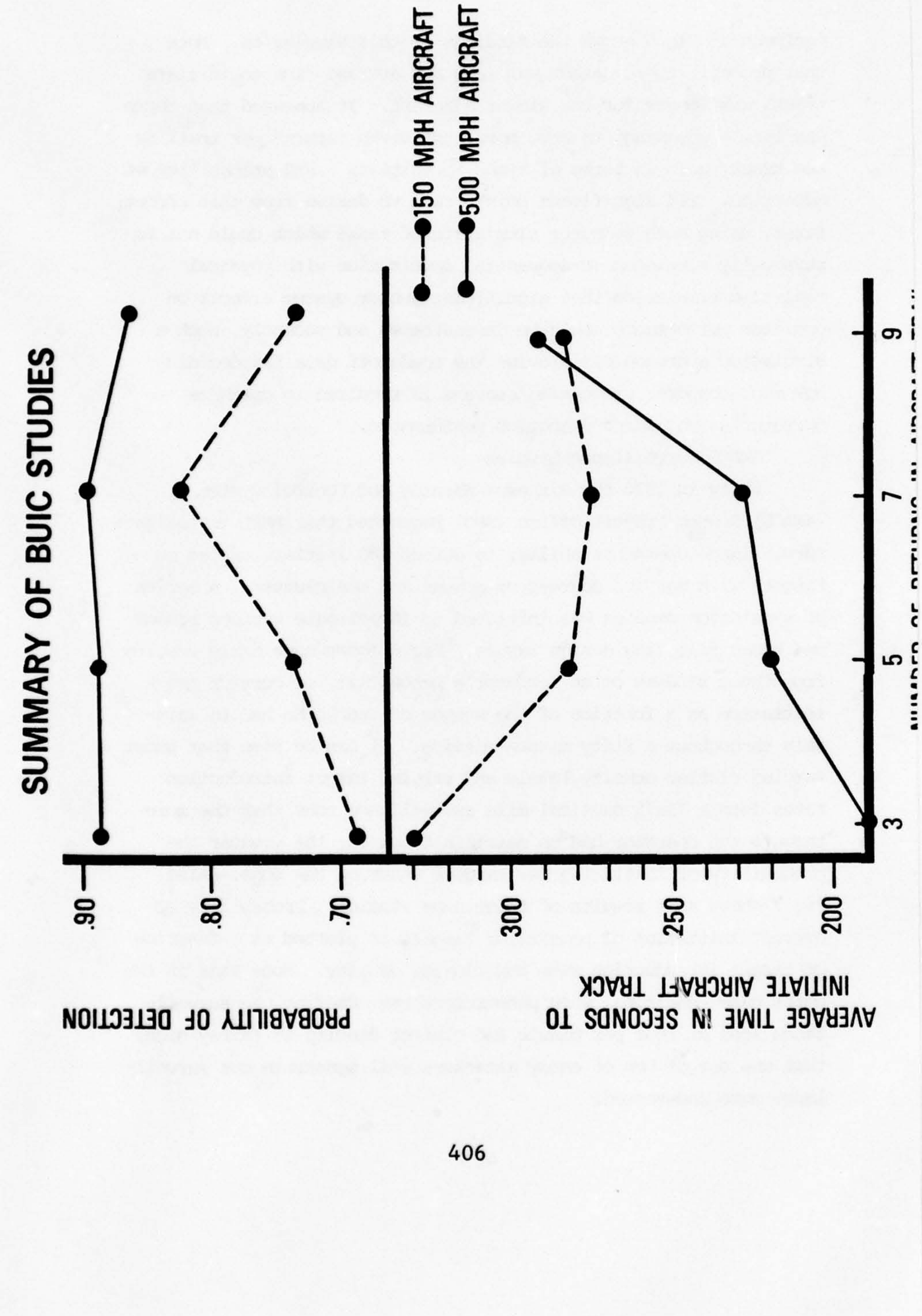
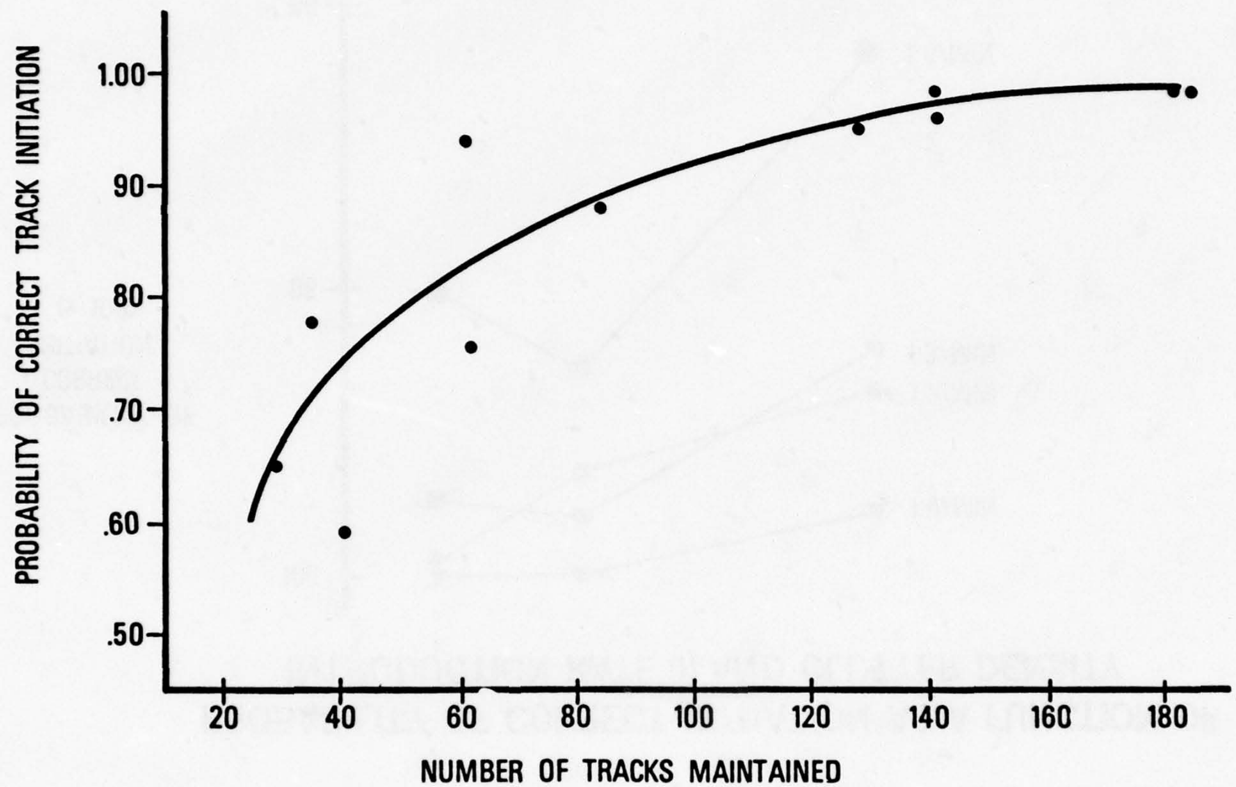
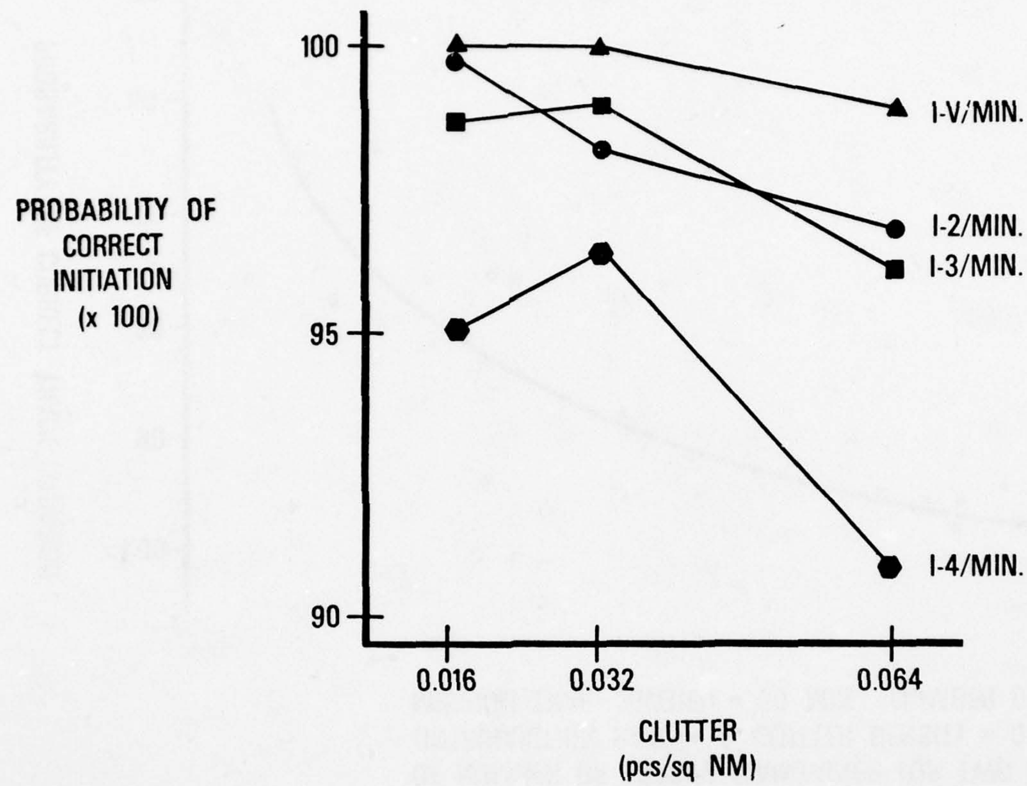

SUMMARY OF BUIC STUDIES
PROBABILITY OF DETECTION
AVERAGE TIME IN SECONDS TO
INITIATE AIRCRAFT TRACK
150 MPH AIRCRAFT
500 MPH AIRCRAFT
.90
.80
.70
300
250
200
3
5
7
9

FIG 6

AWACS DATA – PROBABILITY OF CORRECT TRACK INITIATION AS A FUNCTION OF NUMBER OF TRACKS MAINTAINED FOR TWO MISSION CONDITIONS (INTRODUCTION RATE = 4, CLUTTER DENSITY = 0.16 AND 0.32). MISSION TIME COVERED = 50 MIN. NUMBER OF SUBJECTS = 6.



PROBABILITY OF CORRECT INITIATION AS A FUNCTION OF INTRODUCTION RATE (I) AND CLUTTER DENSITY



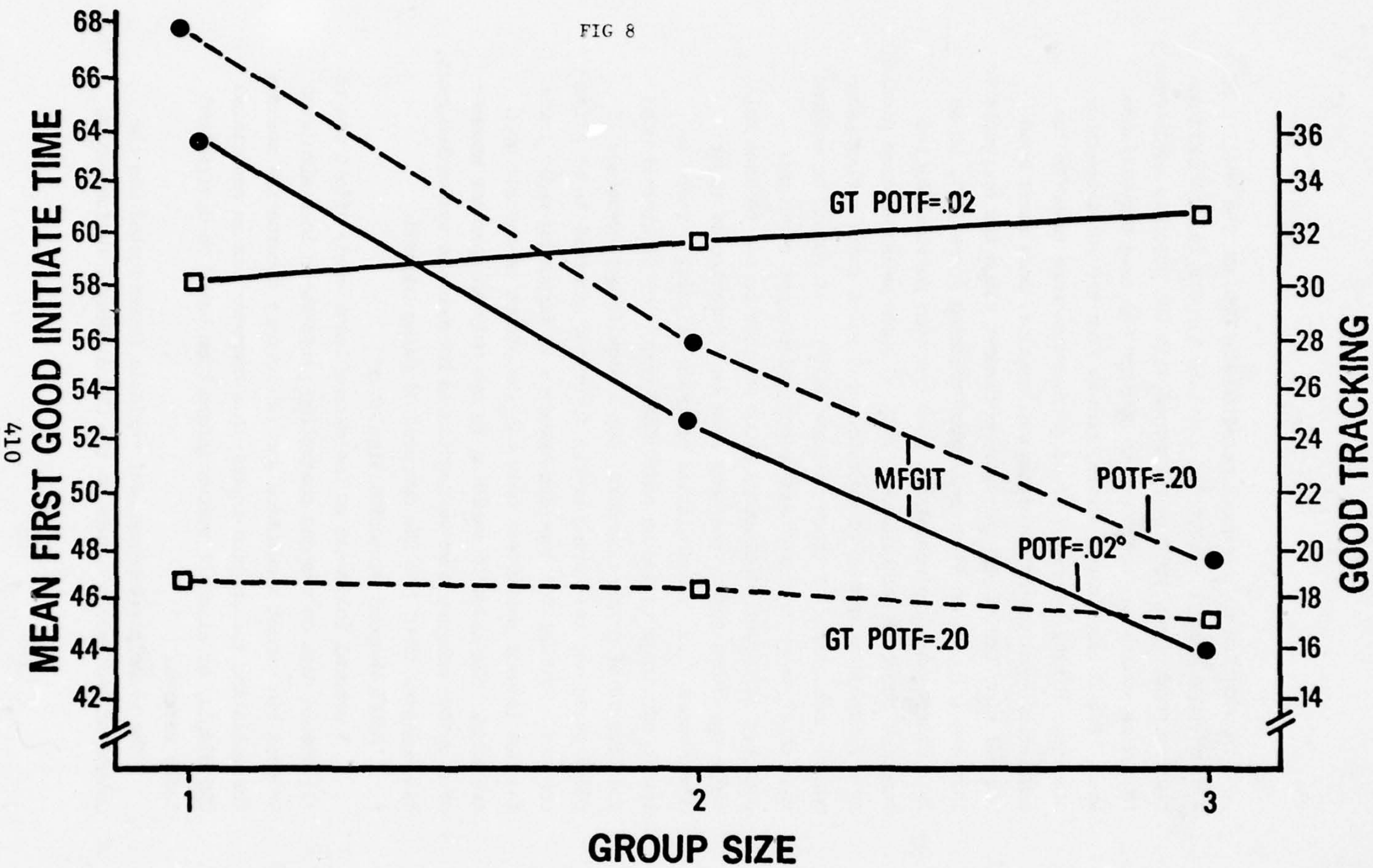
In addition to the questions from the SPO, on the ability of a single operator to detect and initiate targets in high land/sea clutter conditions, we were concerned with the possible advantages in adding additional operators to monitor the same surveillance area. Fig 8 illustrated several points from the multi-operator studies. First, two measures of performance were taken in the simulations--an <u>operator</u> performance measure, mean first good initial time (MFGIT) or the average time it takes the operators to initiate targets and an overall good tracking score (GT), which is a systems measure containing both operator performance and computer tracking performance. Both of these measures were plotted as a function of number of operators 1-3 and a radar system parameter, probability of track failure (POTF). It should be evident that the systems designer and/or commander might reach two entirely different conclusions about whether or not to have multiple operators survey the same area as a function of radar performance (i.e. probabilities of track failure). There is little advantage to adding additional operators if overall good tracking is of primary concern, but a significant advantage if identifying and initiating tracks (operator measure) is of primary concern. Further the expenses involved in improving radar track failure (sensor parameter) only has its effect on overall good tracking. The issue of deciding to use only an operator measure or a system measure must be negotiated between the system designers, R&D managers (SPO) and the operational using command.

• AWACS Weapons Direction Simulation

A natural follow-on to the surveillance study effort was to (1) obtain data on weapons controller performance in a simulated weapons management simulation and (2) compare alternative methods for mediating information inputs to a computer via an associated CRT display of aircraft status information based on digitalized radar returns.

The principle experimental variable investigated was the method of indicating points on the CRT display interface which

FIG 8


MEAN FIRST GOOD INITIATE TIME
68
66
64
62
60
58
56
54
52
50
48
46
44
42
GOOD TRACKING
36
34
32
30
28
26
24
22
20
18
16
14
GT POTF=.02
MFGIT
POTF=.20
POTF=.02°
GT POTF=.20
1
2
3
GROUP SIZE

mediated transferral of data between the operator-controller and computer system. Three methods were investigated: (1) a hand-held pen with fiber optics link to the computer system, (2) a track ball cursor controller, and (3) a force stick cursor controller.

The task used in the simulation required the weapons controllers-operator to direct up to 10 friendly interceptors against attacks by enemy bombers. Five of the fighters were in the air as the simulation began. Each had an airspeed of 500 knots and an altitude of 10,000 feet. The enemy bombers entered from the west side of a 200 x 200 mile area and were distributed randomly along the 200 mile boundary upon entry and traveled in a generally easterly direction toward a bomb release line (BRL) which spanned the display from top to bottom (north to south) at a point 185 miles east of their entry points. Enemy bombers entered with an airpseed of 500 knots and air altitudes of 40,000 feet.

The controller-operator's primary task was to direct the fighters to intercept and "kill" the attacking bombers as far from the BRL as possible. In addition to the experimental variables of light-pen, track-ball and force stick methods of interaction, a second experimental variable of "load" was manipulated. Three levels were investigated. The first load condition was characterized by an attack involving a single wave of 16 bombers. Under the second load condition, 2 waves of 20 bombers attacked with approximately 6 1/2 minutes elapsing between waves. Load three was a single wave of 40 bombers all entering the display area within the first 3 minutes of the session.

The performance measures included: number of kills, average distance from BRL at kill, fighters down for lack of fuel, fuel used and number of operator actions.

Figs 9 and 10 show the comparative effects of the three modes of interacting with the computer generated display as a function of load condition. Note that both in terms of average distance from BRL at "kill" and the fuel used, that the light pen

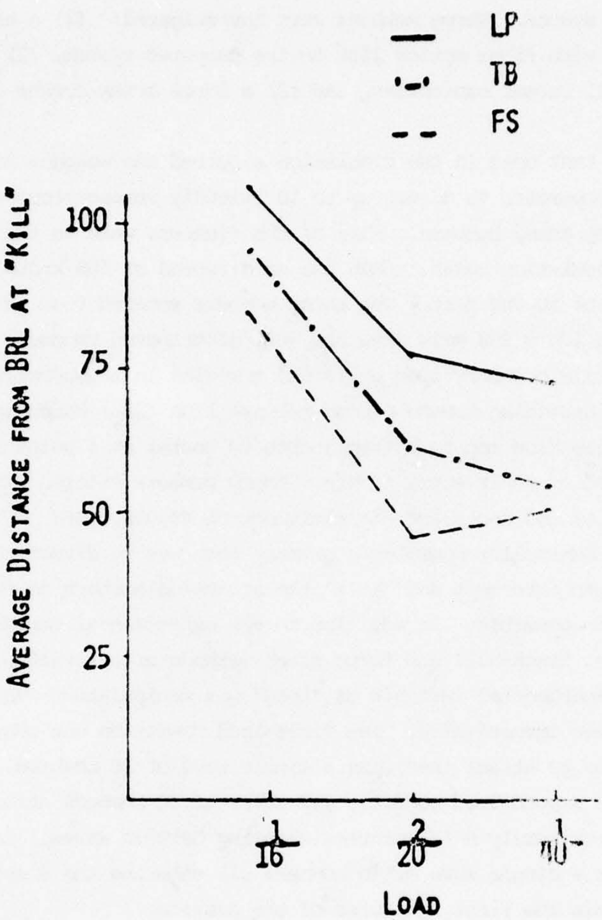


FIGURE 9 Average Distance from BRL at "Kill" For Control Mode and Load.

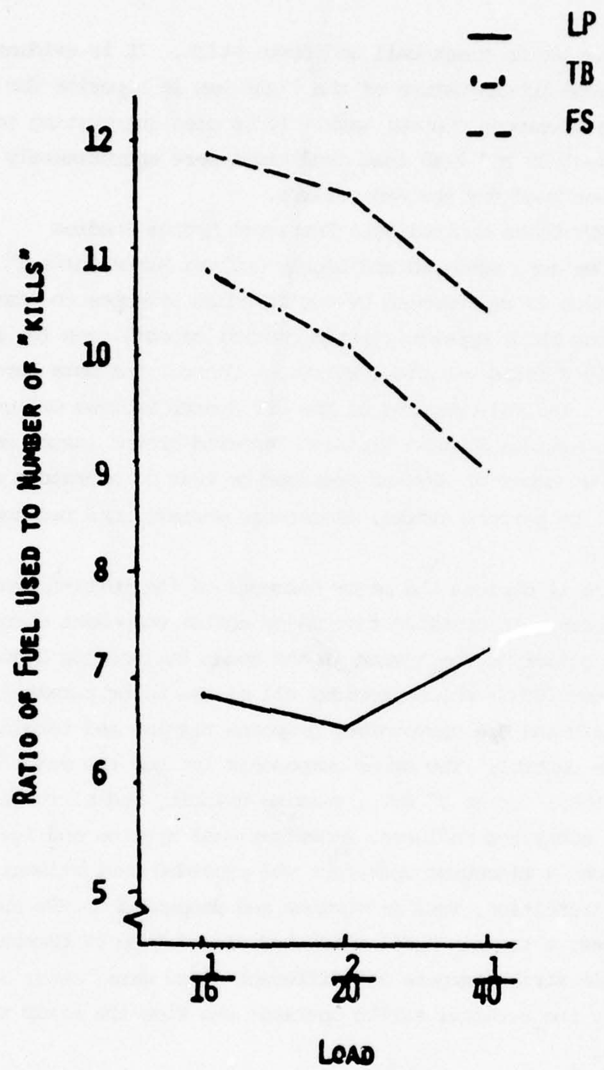


FIGURE 10. Ratio of Fuel Per Aircraft "Killed" by Control Mode and Load.

was superior to track-ball and force stick. It is evident that the random access nature of the light pen is superior for performing a weapons control task. It is also interesting to note that the 2/20 and 1/40 load conditions were approximately an equal workload for the controllers.

•RPV Drone Control Data Retrieval System Studies

Our most advanced and highly evolved Man-Machine C^3 System Simulation is represented by our in-house attempts to answer key questions about operator/system control capabilities for a Remotely Piloted Vehicle (RPV) Drone Control and Data Retrieval System. Initial concerns of the RPV System Program Office (SPO) at Aeronautical Systems Division centered around issues dealing with the number of RPVs an operator or team of operators could control to perform strike, electronic warfare, and reconnaissance missions.

Fig 11 depicts the major elements of the multi-operator RPV simulation. It contains five major system component structures. At the center of the system is the Human Engineering Systems Simulator (HESS) which provides all of the major parametric control, A/D and D/A conversion, graphics display and terminal pilot station control. The other components include the major system parameters: up to 35 RPVs, reading velocity and altitude, 3 data links, subsystem failures, 3 navigational systems and fuel consumption; 4 midcourse operators who provided navigational patches, phase transition, fuel management and responded to RPV subsystem failures; a terrain model which had closed loop TV camera control multiple strike targets and different video data links; and finally the terminal strike operator who flew the birds to the target.

Results from a series of simulations in which system parameters were varied over the conditions of interest to the SPO indicated that operators could control up to four RPVs simultaneously and still meet the navigational cross track error limits and still hand off to a terminal operator at the designated way

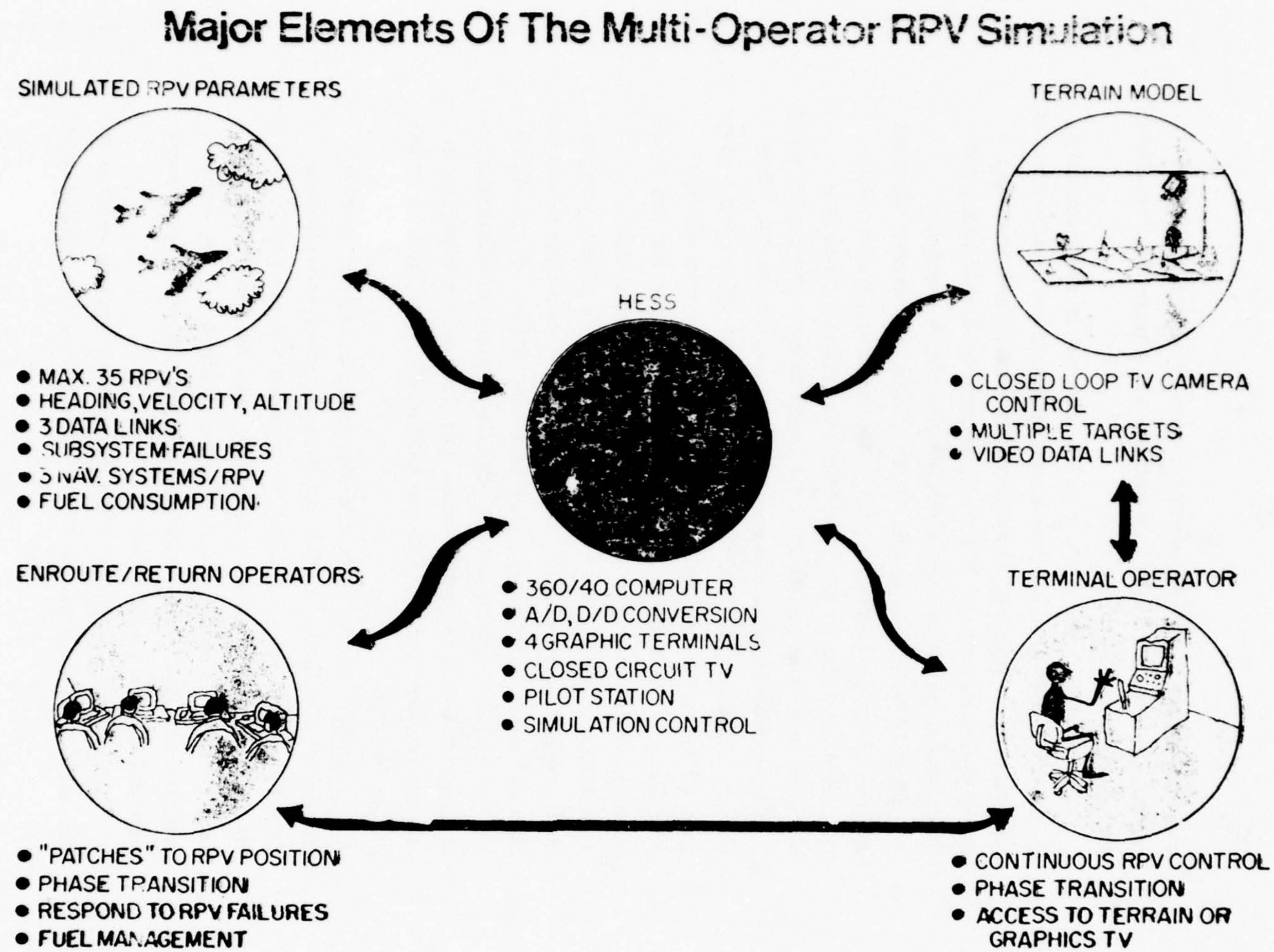

Major Elements Of The Multi-Operator RPV Simulation
SIMULATED RPV PARAMETERS
● MAX. 35 RPV'S
● HEADING, VELOCITY, ALTITUDE
● 3 DATA LINKS
● SUBSYSTEM FAILURES
● 3 NAV. SYSTEMS/RPV
● FUEL CONSUMPTION
HESS
● 360/40 COMPUTER
● A/D, D/D CONVERSION
● 4 GRAPHIC TERMINALS
● CLOSED CIRCUIT TV
● PILOT STATION
● SIMULATION CONTROL
TERRAIN MODEL
● CLOSED LOOP TV CAMERA CONTROL
● MULTIPLE TARGETS
● VIDEO DATA LINKS
ENROUTE/RETURN OPERATORS
● "PATCHES" TO RPV POSITION
● PHASE TRANSITION
● RESPOND TO RPV FAILURES
● FUEL MANAGEMENT
TERMINAL OPERATOR
● CONTINUOUS RPV CONTROL
● PHASE TRANSITION
● ACCESS TO TERRAIN OR GRAPHICS TV

FIG 11

points. However, systems performance could be enhanced by providing automatic heading correction and a means for "smoothing" RPV position reports.

To, in part, verify the results achieved in the operator(s) in-the-loop real-time simulation and to establish verification of our Man-Machine Computer simulation methodology and language; a SAINT (Systems Analysis Integrated Network of Tasks) model and single-team simulation was developed for the RPV system.

Figs 12 and 13 shows the 23 RPV flight performance measures and the 15 operator control performance measures respectively that were measured in the real-time simulation. These same measures were used for SAINT model predictions. The sample model validation/verification results are displayed in Fig 14. Note that in all cases the real-time RPV simulation values for a given team of operators over multiple missions fall within the 95% confidence limits of the SAINT model predictions for the flight performance measures and the operator control measures.
By building a SAINT computer simulation model of such a complex multi parameter and multi-operator system we were able to uncover some defects in the initial real-time simulation. Fig 15 shows the interactive process between physical real-time simulation and computer modeling in pseudo time. Both the system experiments and the systems designer can use and benefit from such an interactive process.

4.0 Summary. In reviewing the fifteen year history of Man-Machine C^3 simulation in the Air Force we might conclude that from the sensed enemy tactical environment through the C^3 system to the Commander or Command authority that the problems fall into three major areas: real-time requirements of the sensed environment; the threat detection process and the threat assessment and command decision making.

Real-Time Requirement - The operational problem rests with the ability to optimize the cycle times between the sensed data

FIG 12

RPV FLIGHT PERFORMANCE MEASURES

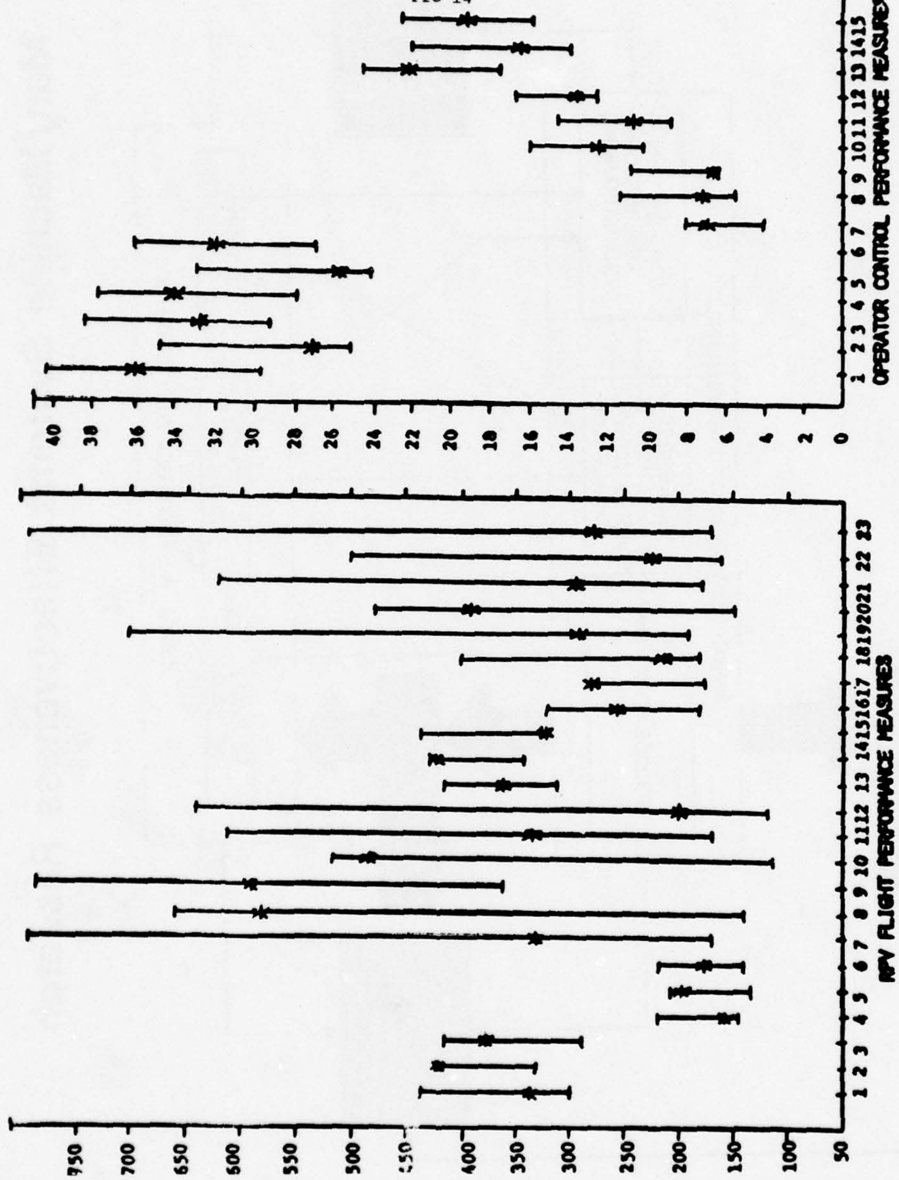
1. AVERAGE CROSS TRACK ERROR DURING ENROUTE FOR S RPVs
2. AVERAGE CROSS TRACK ERROR DURING ENROUTE FOR E RPVs
3. AVERAGE CROSS TRACK ERROR DURING ENROUTE FOR L RPVs
4. AVERAGE GROUND SPEED ERROR DURING ENROUTE FOR S RPVs
5. AVERAGE GROUND SPEED ERROR DURING ENROUTE FOR E RPVs
6. AVERAGE GROUND SPEED ERROR DURING ENROUTE FOR L RPVs
7. AVERAGE CROSS TRACK ERROR AT H FOR S RPVs
8. AVERAGE CROSS TRACK ERROR AT H FOR E RPVs
9. AVERAGE CROSS TRACK ERROR AT H FOR L RPVs
10. AVERAGE GROUND SPEED ERROR AT H FOR S RPVs
11. AVERAGE GROUND SPEED ERROR AT H FOR E RPVs
12. AVERAGE GROUND SPEED ERROR AT H FOR L RPVs
13. AVERAGE CROSS TRACK ERROR DURING RETURN FOR S RPVs
14. AVERAGE CROSS TRACK ERROR DURING RETURN FOR E RPVs
15. AVERAGE CROSS TRACK ERROR DURING RETURN FOR L RPVs
16. AVERAGE GROUND SPEED ERROR DURING RETURN FOR S RPVs
17. AVERAGE GROUND SPEED ERROR DURING RETURN FOR E RPVs
18. AVERAGE GROUND SPEED ERROR DURING RETURN FOR L RPVs
19. AVERAGE CROSS TRACK ERROR FROM S TO H FOR S RPVs
20. AVERAGE GROUND SPEED ERROR FROM S TO H FOR S RPVs
21. AVERAGE CROSS TRACK ERROR AT S FOR S RPVs
22. AVERAGE GROUND SPEED ERROR AT S FOR S RPVs
23. AVERAGE CROSS TRACK ERROR FROM H AT PILOT CONTROL FOR S RPVs

FIG 13

OPERATOR CONTROL PERFORMANCE MEASURES

1. AVERAGE NUMBER OF PATCHES ATTEMPTED FOR S RPVs
2. AVERAGE NUMBER OF PATCHES ATTEMPTED FOR E RPVs
3. AVERAGE NUMBER OF PATCHES ATTEMPTED FOR L RPVs
4. AVERAGE NUMBER OF PATCHES COMPLETED FOR S RPVs
5. AVERAGE NUMBER OF PATCHES COMPLETED FOR E RPVs
6. AVERAGE NUMBER OF PATCHES COMPLETED FOR L RPVs
7. AVERAGE NUMBER OF VELOCITY CHANGES FOR S RPVs
8. AVERAGE NUMBER OF VELOCITY CHANGES FOR E RPVs
9. AVERAGE NUMBER OF VELOCITY CHANGES FOR L RPVs
10. AVERAGE NUMBER OF PATCHES ATTEMPTED DURING ENROUTE FOR S RPVs
11. AVERAGE NUMBER OF PATCHES ATTEMPTED DURING ENROUTE FOR E RPVs
12. AVERAGE NUMBER OF PATCHES ATTEMPTED DURING ENROUTE FOR L RPVs
13. AVERAGE NUMBER OF PATCHES ATTEMPTED DURING ENROUTE FOR S RPVs
14. AVERAGE NUMBER OF PATCHES ATTEMPTED DURING RETURN FOR E RPVs
15. AVERAGE NUMBER OF PATCHES ATTEMPTED DURING RETURN FOR L RPVs

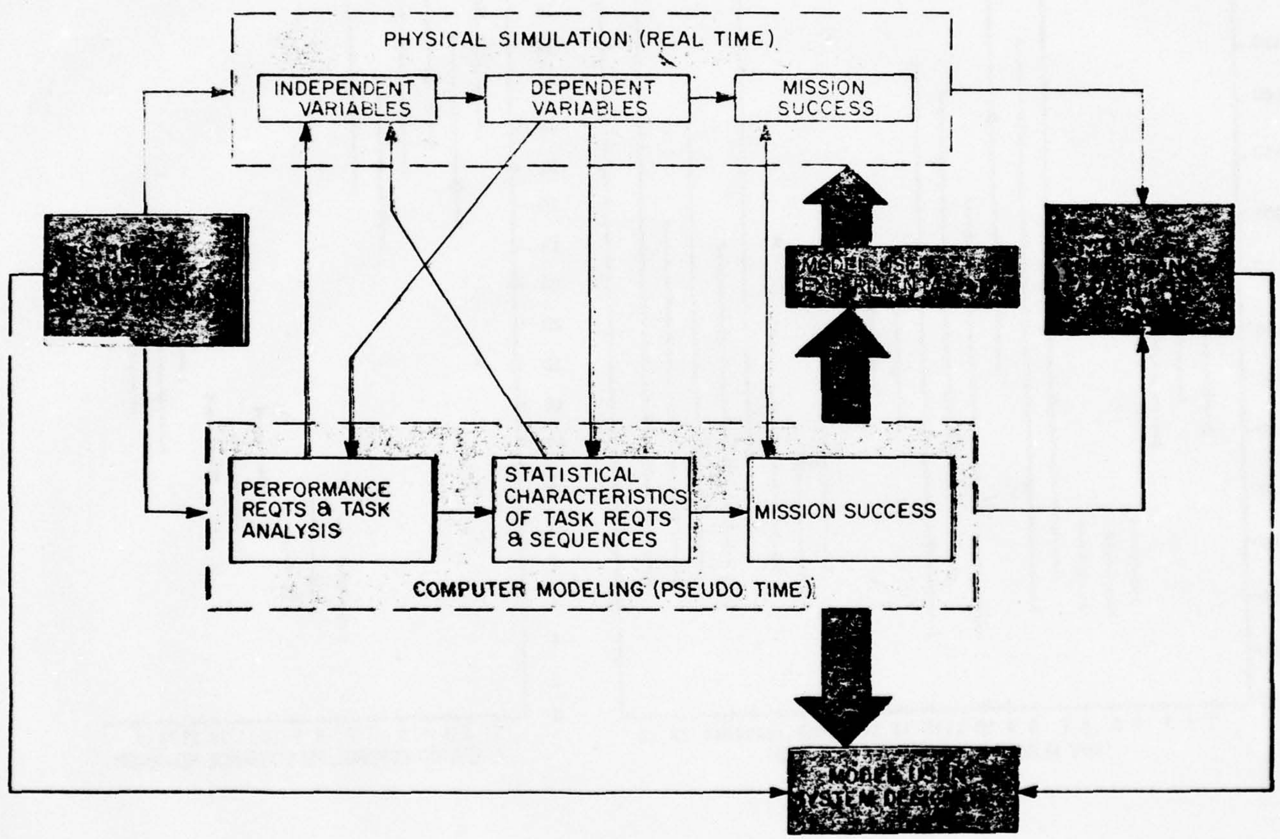
FIG 14



OPERATOR CONTROL PERFORMANCE MEASURES
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40
RPV FLIGHT PERFORMANCE MEASURES
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
50 100 150 200 250 300 350 400 450 500 550 600 650 700 750

FIG 15

Man/Machine Systems Effectiveness Research



in the threat environment and the operator's/commander's ability to gain access to this information in an interactive fashion. The raw sensed data must be processed and transformed into usable information (e.g., track history for surveillance operators or interceptor availability/capability for weapons directors) Normally, it is assumed that the best design is one which minimizes access and cycle time. Evidence from simulations and operational environments suggest that cycle times less than 2-5 seconds for normal digitalized radar surveillance track loads are useless computer capacity. The expense in realizing these high computer speeds may not be warranted in terms of systems effectiveness criteria such as probability of detection P_D.

Threat Detection: The operational problem is that the probability of detection is less than 1.00, $P_d < 1.00$. The causative factors are to be found in hardware (e.g., radar sensing capability, computer capacity and speed, etc.) in human operators (e.g., perceptual discrimination between clutter and targets, ability to handle high target introduction rates, etc.) and software (e.g., radar filtering algorithms, radar correlational algorithms, etc.). Lack of data in these three areas and their interactions make it impossible to specify optimal system design parameters.

Threat Assessment and Command Decision Making: Today full advantage of computerized decision aids is not implemented in command and control systems although they are in effective use in the intelligence community. To assert that maximum decision effectiveness is not being achieved in advanced C^3 systems, implies that a quantitative rather than a qualitative standard of performance can be developed. Such a standard has been developed based on Bayes Theorem, implicit in which computer assistance techniques are available (e.g., the computer can perform certain computations, in this case, data aggregations to unburden the commander in minimizing the uncertainty of the data

available to him which bear on the decision alternatives).

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CASE STUDY IN INTEROPERABILITY MANAGEMENT

by COLONEL THOMAS H. THOMPSON
Langley AFB

1.0 What Is Interoperability? Before starting a discussion of interoperability, let me establish a frame of reference and give you the Tactical Air Forces Interoperability Group (TAFIG) understanding of the meaning of interoperability. Within TAFIG, we use the NATO definition from Allied Tactical Publication 33 as our starting point (Figure 1). We further stress the point made in the DoD definition, wherein "the degree of interoperability should be defined when referring to specific cases" (Figure 2). In other words, interoperability is not an all-encompassing thing and should be distinctly limited to a desired or required level.

Figure 3 reflects the general aspects of interoperability which must be considered when working the problem of defining the desired or required degree of interoperability to be achieved. We have tended in the past to generally consider only the mechanical/electrical interface noted between MODEM's, and typically we expend much effort in wrestling with message formats. TAFIG is working the problem from the data interpretation standpoint by first determining what information is wanted or needed to be exchanged between elements and then working toward the mechanical/electrical connection to accomplish the exchange. In this manner, we believe the system design can be more clearly defined at the outset.

Our viewpoint is supported by the Command Control Information Processing-85 Study, CCIP-85. Volume VIII of this Air Force Systems Command study points out the basic problem: the interface requirements of a system are normally addressed last. As a result, the impact on the system is significant and the degree of interoperability is compromised. This approach toward interoperability

INTEROPERABILITY

"INTEROPERABILITY IS THE ABILITY OF SYSTEMS, UNITS OR FORCES TO PROVIDE SERVICES TO AND ACCEPT SERVICES FROM OTHER SYSTEMS, UNITS OR FORCES AND TO USE THE SERVICES SO EXCHANGED TO ENABLE THEM TO OPERATE EFFECTIVELY TOGETHER. IT INCLUDES COMPATIBLE COMMAND AND CONTROL SYSTEMS, PROCEDURES, WEAPONS SYSTEMS, AIRBORNE AND GROUND-BASED NAVIGATIONAL AIDS, ELECTRONICS, COMMUNICATIONS, PROCEDURES AND EQUIPMENT FOR IDENTIFYING FRIEND FROM FOE, AND CROSS-SERVICING FACILITIES. SUCH A CAPABILITY, BOTH WITHIN AND BETWEEN NATO AIR RESOURCES IS NOT JUST MILITARILY DESIRABLE, BUT IN SOME INSTANCES IS CRITICAL TO THE CREDIBILITY OF THE DETERRENT AND TO THE EFFECTIVE USE OF AIR POWER."

(ATP-33)

Figure 1

INTEROPERABILITY

"(DOD, NATO) 1. THE ABILITY OF SYSTEMS, UNITS OF FORCES TO PROVIDE SERVICES TO AND ACCEPT SERVICES FROM OTHER SYSTEMS, UNITS OR FORCES AND TO USE THE SERVICES SO EXCHANGED TO ENABLE THEM TO OPERATE EFFECTIVELY TOGETHER. (DOD) 2. THE CONDITION ACHIEVED AMONG COMMUNICATIONS-ELECTRONICS SYSTEMS OR ITEMS OF COMMUNICATIONS-ELECTRONICS EQUIPMENT WHEN INFORMATION OR SERVICES CAN BE EXCHANGED DIRECTLY AND SATISFACTORILY BETWEEN THEM AND/OR THEIR USERS. THE DEGREE OF INTEROPERABILITY SHOULD BE DEFINED WHEN REFERRING TO SPECIFIC CASES."

JCS PUB I

Figure 2

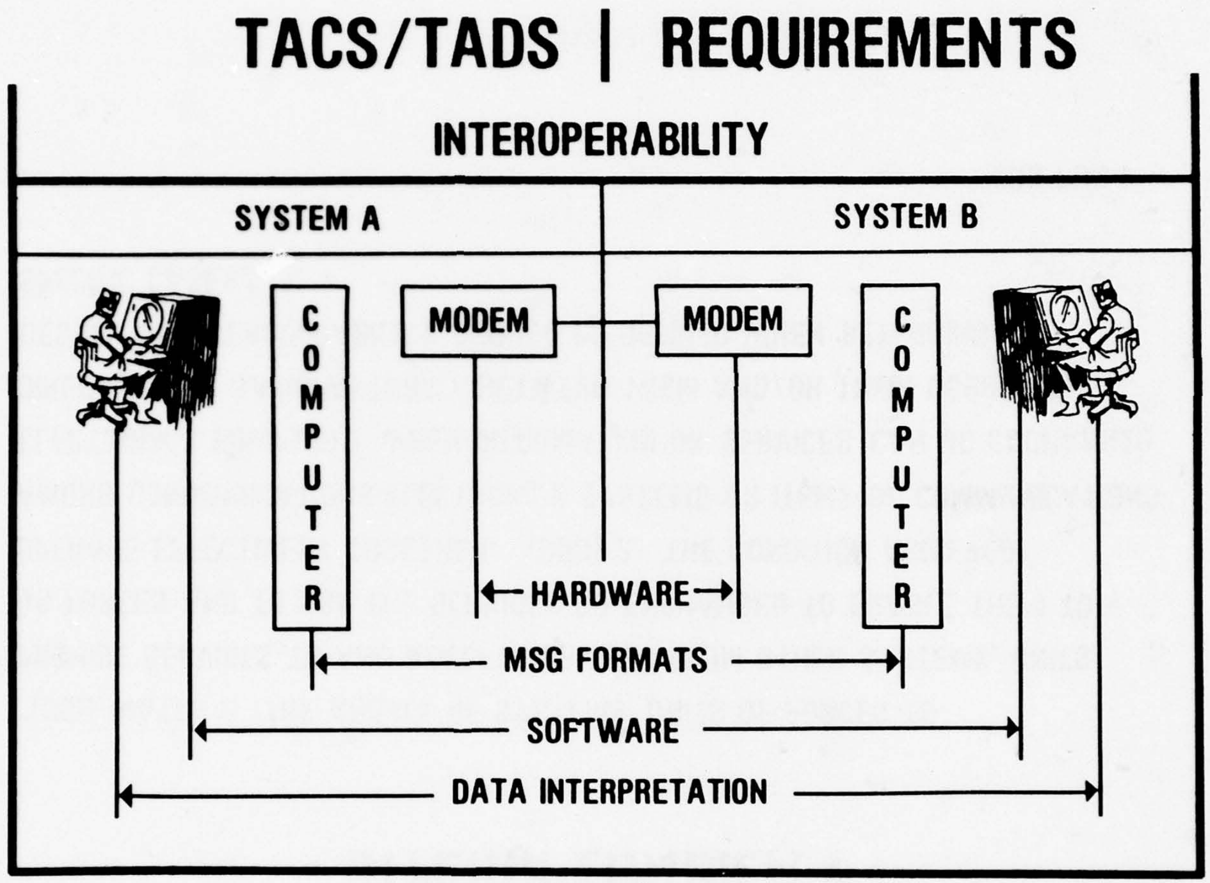

TACS/TADS | REQUIREMENTS
INTEROPERABILITY
SYSTEM A
SYSTEM B
COMPUTER
MODEM
MODEM
COMPUTER
HARDWARE
MSG FORMATS
SOFTWARE
DATA INTERPRETATION

Figure 3

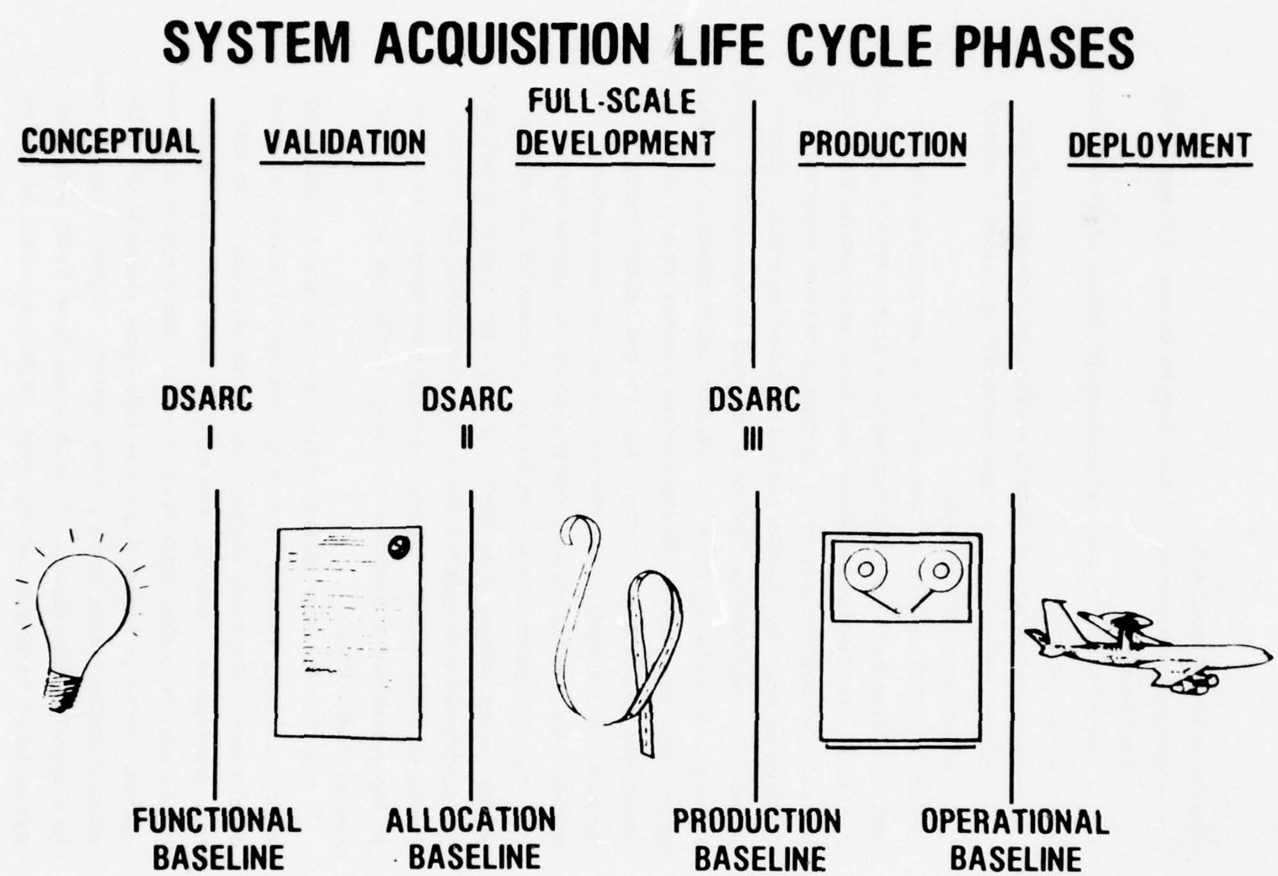
appears to be a result of:

- Inadequate direction by the user as to what systems should interface.
- Inability of the user or designer to define characteristics of an interface.
- Requirements people lacking a detailed knowledge of our own C^2 systems and of other services' or nations' current or projected C^2 systems.

Volume VIII goes on to note that as a result, the requirement or design tends to be conceived as a single system operating by itself. In those cases where interface requirements have been defined, the coordination cycle up through service departments has resulted in only the minimum capability being approved. Interoperability requirements tend to be treated as nonessential "gold plating". A valid objection to defining interoperability requirements early for a system is the obvious problem of having to coordinate requirements within a service and between services or nations. Additionally, interface functions utilize hardware and software which might inhibit further growth or improvements.

The net result is that intra- and interservice interoperability is not addressed in depth until the developing system must be coordinated with other services or processed by the Joint Chiefs of Staff (JCS). Interoperability then becomes an add-on to the system and a deterrent to early fielding of the singular system capability.

The CCIP-85 study clearly points out the need to establish interoperability requirements in the conceptual phases of system development. The study concern was driven principally by software development. However, the point is made that interoperability must be worked throughout the full life cycle of any given system. Shown in Figure 4 are the life-cycle phases with applicable decision points for any large system. Interoperability must be a specific consideration at each stage as we learn about the system being developed and employed. Software, which is the key



SYSTEM ACQUISITION LIFE CYCLE PHASES
CONCEPTUAL
VALIDATION
FULL-SCALE DEVELOPMENT
PRODUCTION
DEPLOYMENT
DSARC I
DSARC II
DSARC III
FUNCTIONAL BASELINE
ALLOCATION BASELINE
PRODUCTION BASELINE
OPERATIONAL BASELINE

Figure 4

to modern command and control systems, follows the same cycle with different names attached, as shown. Management of the baselines with interoperability considered is probably our most difficult task.

Surprisingly, another problem is that current interoperability efforts rely too heavily on the implementation of a common JCS message standard, such as those in JCS Pub 10. The implication is that if a new system implements TADIL-A or TADIL-B messages or a new standard such as that proposed for the Joint Tactical Information Distribution System (JTIDS), interoperability therefore follows.

Although the use of a common message standard is an essential part of interoperability, it is an oversimplification to imply that such a standard is sufficient to ensure interoperability, much less joint operational effectiveness of the interfaced systems.

2.0 How Do We Achieve Interoperability? Now that I have established an understanding of what I mean by interoperability, I will take you through some of the more recent background efforts to achieve interoperability.

Emphasis on the requirement to interface or tie automated systems together appears to have reached a focus in the 1950's, with individual services exchanging digital data between operation centers. Successful interfaces were achieved in the early 1960's by the Army Missile Control System and the Air Force 412L System in Europe. The Navy and Marine Corps also achieved a high degree of interoperability during this same time frame. In the continental United States, the Air Force Air Defense Command SAGE sites successfully operated using data links with Army Air Defense Command Posts. These efforts obviously were unilateral or bilateral programs with limited objectives in mind.

The first major attempt at joint service oeprations was the Southeast Asia interface directed by DoD/JCS in mid-1967. The Air Force was designated as the executive agent, and the Tactical

Air Control Systems employed in Southeast Asia were digitally interfaced using the JCS Pub 10 TADIL as the basis. This interface, born in the press of combat, used systems that each service had independently developed. It put them together through the genesis of _ad hoc_ working groups and the establishment of a special test force to polish the interface prior to deploying to Southeast Asia. The system while deployed continued to grow and improve as deficiencies were noted. One thing became apparent in this program: it required a great deal of coordination by various committees to mutually bend and modify the individual service systems to achieve a workable interface. Also required was an understanding by each participant of the other services' capabilities.

The next major step in the interoperability trail came with the establishing of the TACS/TADS Program. TACS/TADS is an acronym for Tactical Air Control Systems/Tactical Air Defense Systems. The program came about because the Air Force was developing the 407L program to provide an improved, manual control system capability that was mobile or deployable. The other services expressed concern to DDR&E in late 1966 that the Air Force would have only a voice capability for the exchange of information, while they were planning to use digital communications. This concern culminated in a December 1966 DDR&E memo directing the Air Force to ensure that digital links would be available and that these links would conform to JCS Pub 10, Tactical Communication and Control Systems Standards. An _ad hoc_ group was formed in the spring of 1967 to identify problems, and special studies were assigned. With the obvious intention of getting something done in a hurry, service groups attempted to define what had to be done. It quickly became apparent that the services could not agree. The remainder of 1967 was spent by the services trying to reach agreement on this point. By November 1968, Mr. Paul Nitze, then Assistant Secretary of Defense, generated a new program which specifically stated a need for joint testing and demonstration of compatibility and joint effectiveness of the four service systems.

Based on this guidance, the JCS in February 1969 established the Joint TACS/TADS Program, designating the Chief of Naval Operations as the executive agent with the responsibility for ensuring that the tactical interface was achieved and to conduct tests to demonstrate these parameters in an operational environment. The executive agent established a joint interface test force to supervise the development of digital information standards for the several systems and to conduct a test program which would demonstrate that all the systems could beneficially exchange information by data links.

Let me digress a moment and note that at the same time this was going on, a program called WESTPAC NORTH also began and was based on a technical arrangement between the Government of the United States and the Government of Japan relating to the Badge System Program. This program was essentially doing the same thing as TACS/TADS, with the Japanese System, the Navy Tactical Data System and Airborne Tactical Data System, and the Marine Tactical Data System interfacing with the manual Korea Air Defense System and the manual Okinawa Air Defense System. We were obviously learning the advantages of interfacing and also discovering the problems in achievement. I will say no more about this program, as it was less complex than the TACS/TADS Program, which better illustrates the difficulties in interfacing tactical data systems. There is also a significant effort on-going in the NATO community, which is the subject of a complete briefing within itself, considering the international committees along with technical and funding issues.

The Chief of Naval Operations early in 1969 assigned an executive agent and established the Joint Interface Test Force (JITF) in San Diego. JITF, drawing heavily on the people who had worked the previous Southeast Asia interface, established its initial effort as the publication of an Interface Management Plan, a Technical Interface Concept, a Technical Interface Design Plan, and a Joint Interface Test Plan. Our present experience tells us

these basic documents are the kinds of things we need to work interface programs, so I will outline briefly what they are. (See Figure 5.)

The Interface Management Plan establishes management policies, procedures, and organizations. It identifies responsibilities, tasks, and documents required of each participating test unit. It further identifies unique support and program milestone schedules. Probably more important, it establishes a system of interface software configuration control.

The Technical Interface Concept document describes the participating system elements of the interfacing systems - specifically, broad interface configurations - and describes the interface functions in terms of elements of operational information to be exchanged. It also establishes a basis for interface management functions required during the test program.

The Technical Interface Design Plan (TIDP) provides the basic design criteria for the interface. This plan defines and itemizes the messages and data elements to be exchanged, integrates the data exchange implementation plans of the interfacing system, and defines the required interface processing procedures. The plan includes system descriptions, intersystem performance criteria, and systems capability. The TIDP is maintained as the standard for configuration control or management.

The Joint Interface Test Plan establishes the philosophy and scope of the test program. It specifies the test objectives for each test phase and establishes three basic phases. The first of these is qualification testing to confirm that communication subsystems function properly, that data links can be established, and that digital data can be exchanged. Interface design testing is the second phase, and is conducted to prove the design of the interface and to confirm that each service has correctly interpreted and implemented the Technical Interface Design Plan in their respective systems. The third phase, the technical interface concept testing, is conducted to confirm that the participating systems are interoperable and that the interface is ready for an

TACS/TADS DOCUMENTATION

- INTERFACE MANAGEMENT PLAN
- TECHNICAL INTERFACE CONCEPT
- TECHNICAL INTERFACE DESIGN PLAN
- JOINT INTERFACE TEST PLAN
- OPERATING PROCEDURES

Figure 5

operational effectiveness demonstration under field conditions.

The last document on the list concerns possibly the most important facet of interoperability - the development of procedures that "people" operate with. The test force develops procedures that functionally demonstrate the operation of the interface in a test environment. Let me emphasize the "test" environment. Those procedures we develop in this somewhat sterile situation with specially trained people are considerably different from those needed in the field, where we are operating with many levels of skills and several hundred people involved in various parts of the operation. We have found it is necessary to rework and redescribe the required procedures to operate and interface in a field environment with normal field terminology. We sometimes forget the total numbers of people operating in a joint combat force and that their perspective is somewhat different from ours in the test or laboratory world.

Now, obviously, all of this does not happen without considerable committee-type work, and the management organization is established around several committees at different levels to work out the details and achieve consensus. These groups face all of the pressures and concerns generally attributed to group decision-making:

- Expenditures of additional and scarce funds strongly influencing the members' votes;
- Protection of one's self-interest - or "Don't let the blame for failure fall on us";
- The general tendency to bring a panel of experts to protect your negotiator and discredit the other side's approach.

However, there is a feedback loop established in the process, and in spite of all the pressures working, we achieve a level of success.

There are three committees that are key to TACS/TADS management, as shown in Figure 6. The committees operate in a closed

TACS/TADS COMMITTEES

- EXECUTIVE COMMITTEE (SERVICE LEVEL)
  - POLICY DECISIONS, PROBLEM RESOLUTION
- INTERFACE CONFIGURATION CONTROL BOARD (TEST FORCE LEVEL)
  - APPROVES CHANGES TO TECHNICAL DESIGN PLAN
- JOINT ANALYSIS GROUP (TEST FORCE LEVEL)
  - REVIEWS TEST RESULTS AND RECOMMENDS TECHNICAL FIXES

NOTE: EACH COMMITTEE REQUIRES UNANIMOUS VOTE FOR APPROVAL BUT ALLOWS FOR MINORITY REPORT FOR HIGH ADJUDICATION

Figure 6

loop. For purposes of illustration, I will start with the Joint Analysis Group, or JAG. This group reviews the results of testing required in the various phases of the program which I mentioned earlier. Assuming that a difficulty is noted, the JAG evaluates the discrepancy and recommends a technical fix. Once agreed to, this fix is forwarded to the Interface Configuration Control Board for a review of the impact on the various service systems. Again, assuming that the fix is acceptable to all members, their recommendations are forwarded to the Executive Committee at the service level for formal review and approval. This level of action is required for commitment of funding and modification of service programs as required.

If the fix is approved, it then goes back to the Configuration Control Board for incorporation into the Technical Design Plan. It is further verified during an approved test, analyzed by the Joint Analysis Group, and reported accordingly. As noted in Figure 6, unanimous vote is required at each level on any subject. A minority report is forwarded for adjudication, and we have actually had cases taken to the JCS for final judgment.

The important point to remember is that the joint product of interfaced systems can be no better than the weakest link. When you are dealing with various service mission requirements, you are working against those specific needs of a service to meet its own particular mission, which is directed by law. In other words, each service must do its job and has an organization and budget to support that job. Joint or unified commands do not enjoy this luxury and therefore must work toward a median solution for all.

We are approaching the operational field demonstration of TACS/TADS, now scheduled for the spring of 1977. The activity levels are increasing as we bring more and more people into an understanding of their training needs for the interoperation of TACS/TADS. Each participant must understand a considerable portion of the other services' systems in addition to being expert in his own.

3.0 Summing Up. In the preceding pages, I have tried to describe what interoperability is and emphasize that specific levels of interoperability must be negotiated and stated at the inception of a system program. Once defined, extensive coordination is required by a dedicated organization throughout the life cycle of the system from conceptual idea through its continuing maintenance in field operating locations. The TACS/TADS management system is not an ultimate system; however, it works, and a lot of midnight oil has been burned in achieving the working relationships needed.

In clcsing, there is one more thought that I must leave with you, and that is the consideration of interoperability requirements between ourselves and allied nations. This is particularly true in NATO. However, a word of caution is important here, in that our total requirements cannot be driven by that unique environment; we must account for other environments that may be more or less sophisticated.

DISCUSSION

Hartley: Using this system, man-machine system, to evaluate the comparative merits of progress which are employed in the machine part. Is system A better than system B? Or is it just a fact that system A is better than System B for certain operators? How is this resolved. As statisticians, we call that an interaction between the hardware system and the operators. My second question refers to the very interesting PERT simulation. I gather from the slides that he showed that it is a considerably smaller set of activities that are involved than one encounters in operational works nowadays. That means that they are hopeful for the simulation procedure he seems to have developed. Apparently he has the capabilities in the simulation of the branching method which decides on the variables that have occurred in the past and what branch to select in going on to the next activity. This is how I understood this. This is a capability that our analytic solution had not incorporated in the computer program. But it is possible to do so by working out the distributions to reach a particular intermediate node and then, dependent on that distribution in the decision rule and then go in either one branch or the other. Therefore I believe that this branching rule involves a decision rule, if I understood him correctly, depending on the variables that he has already encountered. Is it possible to incorporate such an interesting feature in our system?

Topmiller: The first question was addressed to how we handle any unique characteristics of the operators and how that may influence overall systems performance. Typically we do not use operational people as subjects in our simulations. What we do on the RPV simulation for example, our subjects were trained in that simulation for about six months. So they became almost as expert on that system as any operational people might be on their system and we train them all to asymptotic levels on all the performance

variables that we considered significant. So we tried to shrink any kind of between subject variance that may influence our experimental outcome. That was our strategy and it seemed to work fairly well. In several cases we didn't trust ourselves so we called in operational people, particularly in our AWACS simulation, since the RPV system is purely a hypothetical system. The Air Force does not have a RPV system. We build one for them in a simulation context. But in our AWACS simulation, particularly our surveillance and weapons direction simulation, we did bring in an operational group. Typically we find that our highly trained and naive subjects, when they start, are more effective operators overall than are the operational people. Now arguments for the operational people, that they have to unlearn a lot of their operational procedures to learn our hypothetical system. Well, our whole strategy is to try to shrink between subject variance.

The second question, I believe, is addressed to the Saint modelling technique,and I underscore the term "technique". The two composite features of it is the ability to use the network branching logic which covers not only the deterministic type branching. The reason we do this is that for any operator task in a series of tasks his taking a particular action, may be dependent on something which occurred in the system or his previous operation in the system. So when we go into an activity or node description we triger that node depending on what has gone on previously in the system or in a feedback loop. We have approximately six different branching logics. The last part of your second question I was going to give a briefing on SAINT. I won't go into a great briefing on Saint, because in the limited time I could not go into enough detail to answer your question as well as it should be. The other feature of Saint is that we can handle up to 11 different distribution types covering Gaussian through Beta through a variety of distributions that we

feel are necessary to characterize not only operator performance but also machine performance. Typically, you find in many operator actions that you cannot assume the normality of the distribution of whatever measure you are taking. More often than not, if you are dealing with operator times as a measure, you find it can be found to be lognormally distributed. To try to make any generalization in a Monte Carlo type of simulation context, you have the distribution characteristics that fit the particular activity that you are trying to measure.

Dockery: This question, I guess, is directed at the systems panel. There are three papers which I have just heard. One of them was from the gentleman from Perceptronics. He talked about the model of the commander. If I take his work and say that that was also to be useful to building a computer model of the enemy commander, then I think I can introduce a different dimension. The machine has given me a different dimension that I didn't have before. If I take the one that we have just been talking about, Hess, I have just seen a time-lapse film of an entire command and control scheme which does not have a lot of previous analogs which has jsut grown up. The last paper I heard about TACS/TADS and the ultimate weapon in command control is the committee. All three of these are under the umbrella of command and control and I would almost like to challenge the system panel, chaired by Dr. Miller, to draw me the boundary, to begin to compartmentalize, so some sort of structure can begin to emerge from the system. To summarize, I saw in three talks a new dimension of growth in the development area and something which is never thought of in C^2, the committee, which is clearly out there working in the background.

Bracken: I understand that Mr. Robinson is not going to be here tomorrow. I was hoping that he would be because his interests are, in my view the closest of what I regard the main problems that we are here for. He has discussed a number of things. To enlighten General Creech's talk about how in his judgment the Air

Force was in roughly the right balance of command and control investments and personnel as compared to analysis systems and their allocations. I regard that as the major problem we are here to talk about in the Army, Air Force and Navy. What I would like to ask you is if as a principal scientist in the general purpose forces division in Air Force Studies and Analysis, you were asked to analyze a trade-off problem involving command and control system right now with existing models, let us say trading off 100 F16's against some investment in command and control. Just how would you go about doing that?

Robinson: I think that there is a lot that can be done with pencils and papers and serious thought. For instance there are a number of projects that I am aware of but don't want to get involved in that are starting with the construction of time lines and whether or not information is delivered in adequate quantities of the right kind at the right place. I think that is the place to get started. It does not require an elaborate model to get into it at the beginning. I think that the models that exist today don't allow us to examine any decisions. We can get certainly some help in examining the relative contributions of F16's and command and control systems. We would have to have models of aircraft engagements and so forth. I am still going to tie this together with pencil and paper and some hard thought. That is what we have to do today.

Bracken: Have you ever done this sort of study?

Robinson: I would imagine that if we are working on the information system that would be enough. A trade-off of F16's? No, I have never done that one.

Bracken: What do you think of possibly having a computer model which would simulate both?

Robinson: In a straight sense, I don't think that we have any reasonable prospect for a model to do marginal tradeoffs of anything, let alone right now. As you know, the techniques that allow for optimization are fairly limited in scope and allow some

appreciation of some aspects of the problem, but they are so limited that we have to leave out so many things. You look at it and you say it is interesting and I have a new insight, but I haven't really solved the problem. I don't think the model that I am talking about is a model for trade-offs either. It is a model for learning. We don't know - I don't think anybody knows - how to build a model to do trade-off of margins in a very serious way except for some certain special problems.

Bracken: So, do you think they should be left up to the judgment of the President and the Secretary of Defense, the JCS, and the service leaders?

Robinson: Yes, to provide the best advice and insights that they can.

Col. Thompson: Let me give you one comment along that line. What we are trying to do is figure out what command and control is. I noted in the discussions here a mising up, if you will, of what command is. We speak very blithely of the President making a decision, and then we switch right down to company commander and talk about his decision in the same context. One thing that we (TAFIG) are doing within the topic right now, with the help of ESD MITRE - it is a very strenuous effort on our part - is taking apart our command and control system to find out what it is that we do. It seems rather mundane, but when I gather up some of the so called experts in the CRC, which are our Control Reporting Center, radar reporting attacks, and I sat down and I said, all right now, I know what your job is in framt on the scope. Now who do you talk to in the command and control network? So he lists all of the folks that he talks to. And I say, all right, now tell me what you tell those people? So he lists all the things that he tells those people and he also tells me how often he has to say it, what kind of information is being sent back and forth. For example, we go to the TACC, which is our Tactical Air Control Center, and this is where all things are supposed to

happen in the tactical world. We go there and say, "all right, the CRC guy just told me that he talks to you. What do you receive from the CRC?" So then he lists the things that he thinks he receives from the CRC. Now we went through this process and it took us quite a long time by personal interrogation back to that expert, whatever that is, and we put it into the machine and we spun it around, and then put it in a matrix to find out what we were getting out of it and we found that there were 2,000 errors in the questions and answers we got of who talked to whom in the whole network. People don't know who they talk to. They don't know what they exchange. They are really not fully cognizant of what they are doing at any given level - we are going back to functions - very basic functions - and taking the system apart from the level. Asking a guy what he does in a particular engagement in a particular set of things he is working in. Then we start building it back up again. We are also going back to the commander and saying, all right now that you are managing this thing and you are matching force with force. If any of you have the opportunity to listen to General Dixon talk he will tell you a great deal about the big picture and the need of the commander who is in charge, to match his force at a point where it will do the most good against the enemy force. You are going to measure that. Where is that impact point? That is something that you are grouping with here. We had one lecturer talk about anti-submarine warfare. That is also command and control with an infinite level of detail where young captains, lieutenants, and sergeants work. That is the killing portion down there. The generals are concerned with major force application and we have to provide them the advice on where to apply it. The guy down on the lower level is actually killing people and things. We are trying to help him kill more efficiently but we have to find out what they do first. We take a new system and analyze that and put it against what we do now. Maybe we ought to change some of the things we do. In some cases what we are doing before worked very fine - there is

nothing wrong with "Ma Bell" and the grease pencil when it comes to command and control in some things. In others, we need high-speed, digital computers to assimilate a lot of information because it is dependent on the weapons we are using. The point was made earlier RPV control, ballistic missile defense some things happen that fast. I need computers for that. For others, I don't.

Thrall: I have another question for you, Col. Thompson. Some years have elapsed since the military people faced the problem of having ammunition of the same caliber. It started small and it has gone up a little ways. I think there was an agreement in NATO about the size of cannon ammunition for tanks and so on. Now when you showed us your picture of all the computers, it looked to me like a real tower of Babel. Do you see any prospect for getting some of the things you were hoping for, such as maybe a few common executive routines or something? Do you think this is part of the problem of command and control?

Thompson: I'd be naivè to think I could solve that one. However, that worm chart Gen. Dixon uses personally in a lot of his briefings to learned people coming into the command to talk about a lot of these kinds of problems. Every time you look at that and begin to study it a little bit, you begin to think there is no way we can sort it out. But somebody has got to try it. Really, that is what the TAFIG is doing - we are going to try. We are trying to get it into the conceptual stages. That is very important. You must attack at the point when somebody has a piece of paper and there is no contract signed yet. We are already working one system now. We are just past-source selection, and we said, you are buying the wrong thing. They nodded their heads and they understood that they had made a mistake. But it was too late. We are already committed to a multimillion dollar program, and they can't stop it. Now we are worrying about patching it.

Wech: What is your feeling as to why these operators don't quite jive in their assessment of what they are doing? It would appear

to me that that is, in part, a lack of training. If they do it every day, there should be less difference. My question concerns the need for in-house training programs to seek out these trailers in the field.

Thompson: This is probably one of the most critical things we are facing. In TAC, our job is, of course, training. The answer is no, we have not done anything. The reason is that command and control is just on the verge of coming of age, if you will. In command and control five years ago, automation was nonexistent. We worked with grease pencils and telephones. The typical thing was to get a phone call and a guy asked for resources. Then you find them and send them to him. That is essentially what we did. When we had enough folks, bombs and airplanes to do the job, that was satisfactory. But we are in the position of having a minority viewpoint now. We are outmanned, outgunned and outnumbered, so we had better learn to apply things where we want to, where we think it will do the most good. This means we develop sophisticated command and control systems to sense where the enemy really is, where his softest spot is, and go after it. But I have not found a command and control AFSC. I think probably the Navy is the lead service in developing command and control people. Even they are having trouble retaining the people. It is very unglamorous work. They stick a guy back in some dark room someplace in the middle of the ship. All he sees all the time is some idiot display. He keeps punching buttons and talking to guys. He has no sense of satisfaction in the whole thing. In the Air Force and the Army, we are doing the same thing. They tend to come into it and get out of it. There is no glamor. It's sheer suicide as far as your career goes, because the minute you start doing this thing very long, you lose visibility. So people get out of the field right away. As I said, I think the Navy is very far ahead of us in this. They have some very good training mechanisms at Norfolk and San Diego. They do, I think, a nice job as that sort of thing goes.

Richard Pew: This question may be a bit naive. Isn't it possible to think about the problem the other way around? Not so much as building the system so they can interface properly but rather thinking about designing a device which I would say is analogous to the imp in the ARPA computer network which matches one host computer to another. I know there is effort to try to make it possible to access a data file in another computer and make that process transparent to the user in another location. That general concept might be applied to your worm chart.

Thompson: Yes, we are working on that kind of thing, where it can apply. You have to recognize that command and control systems sort of thing where they have access to a file. A command and control system, as I think of it, is a demand response system. I tell you something, I expect a reply back. I give you a certain question or I give you a certain command that calls for a reaction, a demand or response back to me in another nomenclature. I say "Engage" and you tell me how you are doing it and when. Or you tell me you are covering it, for example. That is our problem. Our systems work on the logic to support that. When I get a buffer in here - like you mentioned in the ARPA network - I have to build an entire system on both sides of the buffer so it understands. We are in a very serious problem in Europe now. It was mentioned earlier that we were building a 407L mobil TACS into Europe. It seemed simple enough - we were going to exchange radar data. Unfortunately, the Europeans use a different track numbering system than we do. The very translation of track numbering is a completely different logic. It became a very difficult task, softwarewise, to build a translator in there. We had to modify our system to accomplish this.

Modrick: I think you were talking about a very important point on that diagram. It is showing command communication links, but not really showing the base level of information processes that support that. Would you not also have a large input of informa-

tion requirements into each one of these sources or buffers in order to support the decision and command and control that are being communicated over the links you just showed there?

Thompson: It is quite true, we do. In other words, almost every one of those lines is actually three or four or, in some cases, eight actual links with information flowing in of varying types. It is very true, and I have further breakouts, but that gets into the classified area of what is on those links, and, specifically, the rates we are exchanging at, what information is in it. It is far more complex than shown.

Col. Pride: I don't know if I have a question. If I have a question, I don't know who I want to ask it of. Maybe I just want to voice a wail of frustration because until four months ago I was the commander of the command and control system in Europe. All those lines belonged to me. Every one of those lines represents the third C, the C that comes after command and control, and that's communication. In our attack on the solution of problems, we sometimes assume away that portion that we recognize that we can't solve. What I'd like to know - and here's where I don't know whom to ask - is, were I still the commander, who are you and what are you doing to give me some reliable and survivable communications, so that my command and control system, whatever it is, is going to work five minutes after the first bombs drop?

Thompson: I'll duck that.

A SUMMARY DESCRIPTION OF THE
VECTOR-2 THEATER LEVEL CAMPAIGN MODEL

by SETH BONDER
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1. Introduction. Based in part on its work in modeling small unit combat activities, the Weapon Systems Evaluation Group (WSEG) initiated a program with VRI in the fall of 1972 to develop theater level campaign models that did not involve the use of "firepower score" concepts. A prototype model, VECTOR-0, was completed in August 1973 to demonstrate the feasibility of modeling this level of activity without the use of firepower scores. The first production version, VECTOR-1, was completed in September 1974, and its preprocessor (which computes some of the VECTOR-1 inputs from more basic weapons data and ties directly into the NITFAM-3 data base to directly use its order-of-battle data) was completed in January 1975. The VECTOR-1 model is currently operating on a number of government computers including the HIS 6080 of the Command and Control Technical Center[1], for which extensive documentation was prepared. A sector of the VECTOR-1 model was extracted and enriched for use as a Division Level Model (DIVOPS) in a number of Army studies including the Army Requirements for Air Force Close Air Support and the REMBASS Cost and Operational Effectiveness Analysis.

VECTOR-2 is the second in the series of production model developments to simulate two sided theater level mid-intensity campaigns involving both ground and air forces and systems dynamically interacting on both sides. Specifically, we were asked to add first order effects of command and control, communications, and intelligence to the first version, VECTOR-1, which already had the first order effects of many of the combat processes them-

[1]Computer facility that supports the Joint Chiefs of Staff.

selves. As you will see in a moment, in order to incorporate the command and control, intelligence and communication processes, VECTOR-2 turned out to be a totally new structure (as compared to VECTOR-1) in the manner in which we had to consider the battlefield geometry, forced employments and locations, the command hierarchy, and the timing of the various combat and combat related process events.

Before describing some of the model content, I should hasten to add that the model still does not include explicitly a number of relevant phenomena, including non-integral feedback situations[1], tactical nuclear warfare, and explicit representation of electronic warfare (although elements of this can be implicitly played). It does not include some elements of command and control specified by General Welch and Mr. Robinson at this conference, but which are to be included in the eventual development of the Combined Arms Simulation Model (CASM).

Although VECTOR-2 has not been exercised in a full theater level 100-day campaign, it is clear from our analyses and studies with previous versions of the VECTOR-series models and parts of them (i.e., DIVOPS) that tactical decision behavior (i.e., tactics) have a significant effect on the campaign results.

2.0 Concept of Vector. The overall concept on which VECTOR-2 is based is illustrated in exhibit 1. A commander at any level of the theater command hierarchy has available as input to his decision-making process a desired state of the world (often stated explicitly in terms of a mission which he is to accomplish) and a perceived state of the world (which includes his perception of friendly and enemy force strengths and deployments and his perception of the area of operations in which these forces are deployed). Given this information, the commander makes decisions

[1]Those situations which involve intermingled Blue and Red forces such as deep penetrations and exploitations, sieges, air drops, flank combats, etc.

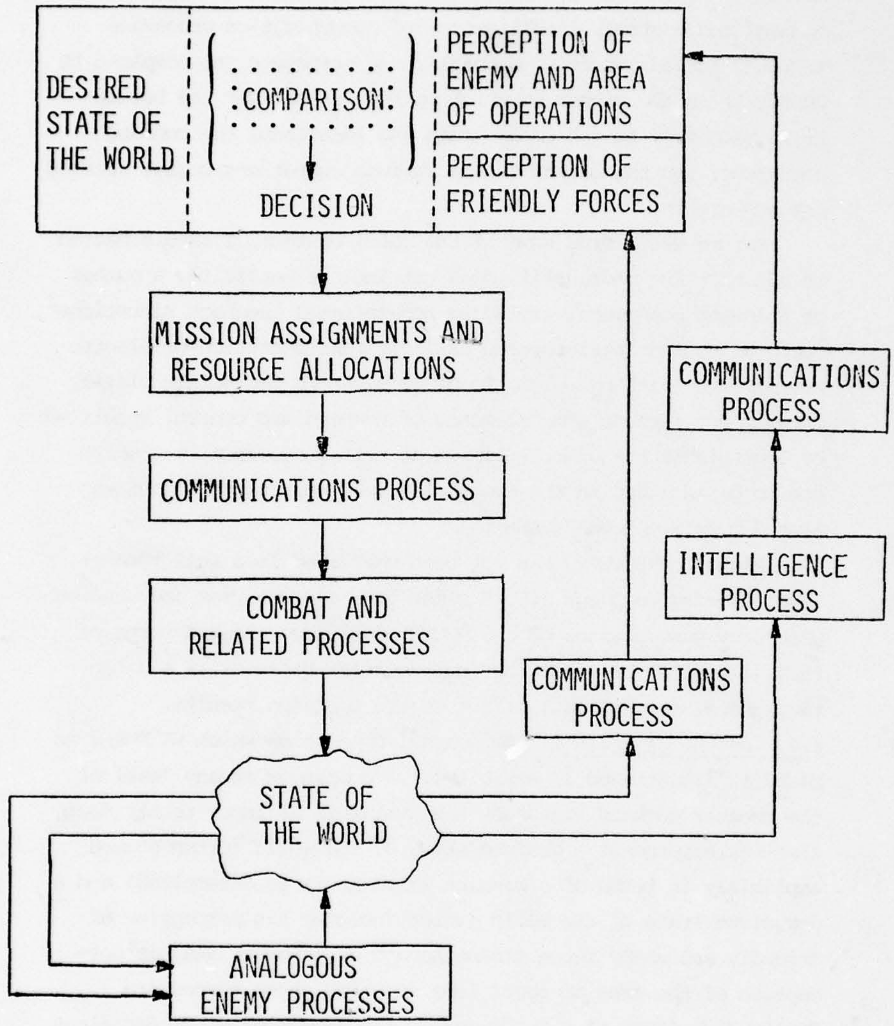

EXHIBIT 1: VECTOR-2 CONCEPT

which are designed to attempt to change the perceived state of the world in such a way that it matches the desired state of the world. These decisions involve the assignment of submissions to lower-echelon units and the allocation of resources to accomplish these submissions. Such decisions are transmitted by a communications process (resulting in a possible time lag) and eventually are carried out in such a way as to affect combat and related processes. These processes (and an analogous set of processes on the enemy side) affect the actual state of the world by changing force levels and deployments for both Red and Blue. Information concerning the resulting new state of the world is transmitted by means of communications processes and (for some of the information) intelligence processes, resulting in the commander revising his perception of the current state of the world. Note that at a given point in time, this perceived state of the world may differ from the actual state of the world as a result of decision lags, communications lags, and imperfect intelligence. The commander then may make new decisions in a further attempt to match the desired and perceived states of the world. This feedback control system operates continuously at all levels of the command hierarchy.

In VECTOR-2, the perceived, desired, and actual states of the world are all represented by sets of variables known as "state variables". These variables describe all aspects of the state or status of the engagement at any time during a run of the model, including the commanders' perceptions of the actual status and their desired statuses. Initial values of these state variables describe the battlefield prior to the initiation of combat The state variables are updated as the combat progresses by a set of process models, which describe the processes of tactical decisions, communications, combat, intelligence, etc. VECTOR-2's state variables are described in section 2.1 of this paper; its process models are summarized in section 2.2.

2.1 Representation of Statuses in VECTOR-2. The following subsections describe the way in which VECTOR-2, through the use of state variables, represents the status of the campaign at any time during a run of the model.

2.1.1 Forces. VECTOR-2 considers Red and Blue maneuver forces, field artillery forces, air defense artillery forces, tactical fixed-wing air forces, and attack helicopters. Maneuver forces on each side can contain up to 11 weapons[1] plus personnel and can employ minefields. Typically, maneuver-unit weapons are represented by two armor (tank) systems, three antitank systems, an attack helicopter system, infantry with rifles, infantry with heavy automatic weapons, infantry with area fire weapons, and two air defense artillery systems. Field artillery forces can contain up to five[2] weapon system types and associated personnel. Air defense artillery forces can contain up to six types of weapon systems and associated personnel. The tactical air forces are comprised of up to seven types of fixed-wing aircraft and associated personnel. Aircraft at airbases may be sheltered or unsheltered; each side may have up to two specific types of aircraft shelters (each of which is dedicated to a single aircraft type) and one general-purpose type of shelter (which can house any type of aircraft). Attack helicopters and associated personnel are available as a fire support resource as well as being utilized as one of the maneuver-unit weapons. The model continually keeps track of the current inventories of personnel and weapon systems by type and location. It also keeps track of the command hier-

[1]A "dimension changer" is currently being designed that will facilitate automatic changes in dimension limits (e.g., increased types of field aritllery, reduction in number of sectors used in a study, etc.). Dimension limits noted in this paper are those that have been used in the development process.

[2]A mortar is currently represented as one of the FA weapon system types.

archy of maneuver forces from theater down to battalion level.

In addition to the above combat elements, VECTOR-2 represents 14 classes of observation resources along with their associated personnel for collecting target and enemy order-of-battle intelligence. Command posts and associated personnel are also represented.

2.1.2 Supplies. Supplies of the following kinds are separately represented in the model: ammunition for each army ground weapon system type, land mines, ordnance (in up to eleven user-specified categories for each side[1]) for aircraft, (including attack helicopters), aviation gasoline and associated POL (for fixed-wing aircraft and attack helicopters), POL for ground systems, and a single category of other supplies.

2.1.3 Battlefield Geometry. VECTOR-2 considers the battlefield to be divided into up to seven sectors running through both Blue and Red territory (see exhibit 2). Red territory is assumed to be divided from Blue by two lines within each sector. These Red-Blue dividing lines are referred to individually and collectively as the FEBA. The FEBA on each side marks the forward edge of front-line forces on that side.

Each sector can be divided into areas which are called combat arenas (see exhibit 3). Within limits, the widths of arenas can vary, but the width should be sufficient to conduct an independent defense (approximately battalion size). Each sector may contain up to 15 arena "ribbons" or corridors. Natural or man-made defensive features (e.g., rivers, mountains, cities, or crossroads) or other designated objectives constitute the end boundaries of the arenas within a corridor. Specifically, any feature which, if defended, requires a particular task force organization to be defeated can be an arena boundary. These boundaries constitute possible objectives for Red and Blue. An

[1] These may be configured into up to ten ordnance loads on each side.

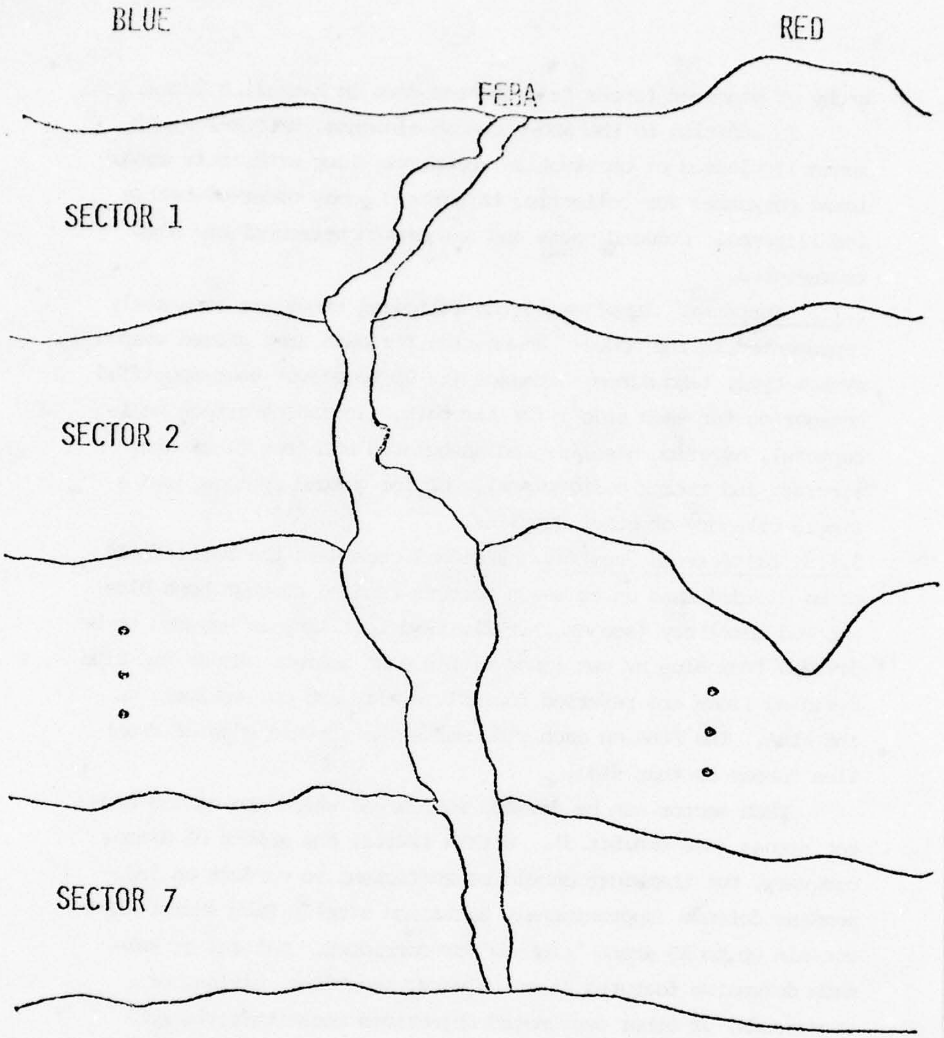

EXHIBIT 2: BATTLEFIELD GEOMETRY -- THEATER

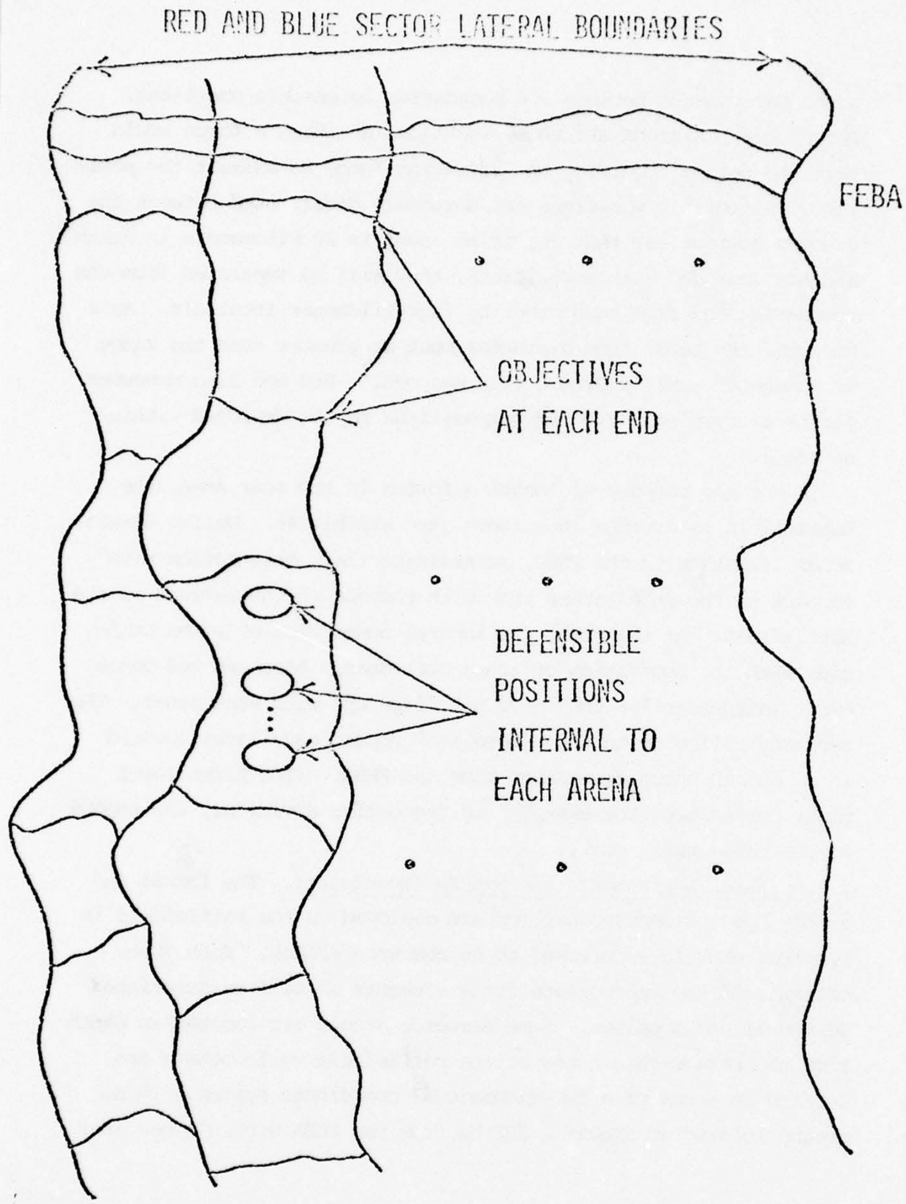

EXHIBIT 3: BATTLEFIELD GEOMETRY -- COMBAT ARENAS

arena may possess between its boundaries defensible positions. Defensible positions are those locations at which a force would halt and defend requiring an advancing force to assault the position. Defensible positions are uniformly distributed between the arena's boundaries; that is, if an arena is 20 kilometers in depth and has four defensible positions, they will be separated from the boundaries and from each other by four-kilometer intervals. As a minimum, the separation distances must be greater than the range of a maneuver unit's direct fire weapons.[1] Red and Blue maneuver forces of varying sizes and compositions may be deployed within an arena.

For the purpose of locating forces in the rear area, the battlefield is divided into zones (see exhibit 4). Unlike arenas, zones "float" with the FEBA, maintaining their orientation with respect to the FEBA rather than with respect to the terrain of the battlefield. At the FEBA, the lateral boundaries of zones coincide with the boundaries of arena corridors. Blue and Red zones exist independently; they need not "line up" with each other. The user may define up to three levels of zones, each level located in a band in successive depth from the FEBA. (The first level might correspond, for example, to front-line divisions, the second to the corps rear, etc.).

2.1.4 *Force Deployments and Supply Inventories*. The forces and supply types discussed earlier are deployed on the battlefield in physical groupings referred to as resource groups. Each group consists of the appropriate force elements as well as associated personnel and supplies. Some resource groups are located in depth from the FEBA within zones of the battlefield while others are located in terms of a two-dimensional coordinate system. Those groups located at specific depths from the FEBA within zones are:

[1]This is to prevent a direct-fire engagement from occurring while opposing forces are both on defensible positions.

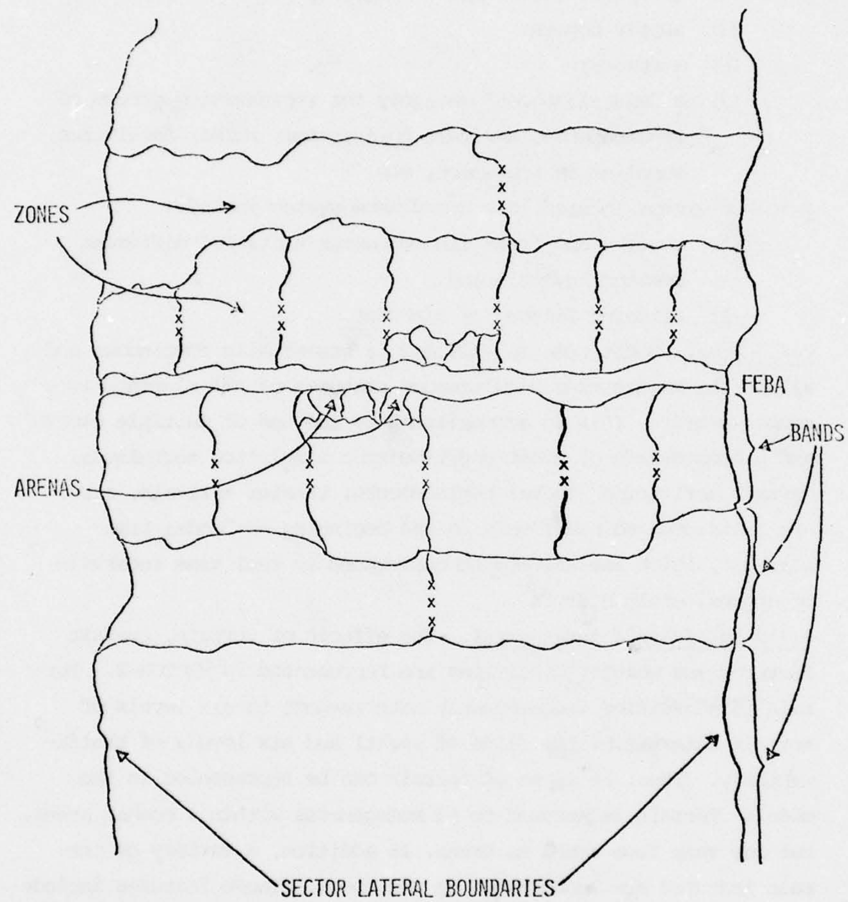

EXHIBIT 4: BATTLEFIELD GEOMETRY -- ZONES

(1) field artillery batteries;

(2) air defense sites;

(3) helicopter bases;

(4) groups of observation resources;

(5) supply depots;

(6) airbases;

(7) a "miscellaneous" category for representing groups of replacements, arrivals to a sector, repair facilities, supplies in transport, etc.

Resource groups located in a coordinate system include:

(1) reserve and front-line maneuver units (of different command levels); and

(2) airborne flights of aircraft.

2.1.5 Time. Model time in VECTOR-2 is essentially continuous and allows for maintaining simultaneous statuses of all elements in a combat sector. This is accomplished by the use of multiple clocks[1] and a combination of event and time step simulation techniques. Certain activities (sector replacements, theater arrivals, etc.) are restricted to occur only at the beginning of "model time periods", which are assumed to correspond to real time intervals of approximately a day.

2.1.6 Battlefield Environment. The effects of terrain, terrain features and weather conditions are represented in VECTOR-2. Terrain is classified independently with respect to six levels of terrain intervisibility (line of sight) and six levels of trafficability. Thus, 36 types of terrain can be represented in the model. Terrain is assumed to be homogeneous within a combat arena, but may vary from arena to arena. In addition, a variety of terrain features are represented in the model. These features include

[1]The clock time steps can be set by the user. The model is currently operating with 30 second, three minute, fifteen minute, one hour, and six hour clocks, in addition to the "model time period" of a day.

urban areas, rivers, and an unidentified terrain feature that can be specified by the user of the model. All terrain features are located at the end boundaries of combat arenas.

Weather conditions in each sector of the battlefield can be input to the model for every hour of simulated campaign. Weather is represented in terms of four levels of each of the following characteristics:

(1) weather visibility for ground-to-ground operations;

(2) weather visibility for ground-to-air and air-to-ground operations;

(3) weather visibility for air-to-air operations;

(4) weather trafficability for ground operations (used to represent the effects of adverse weather conditions such as rain or snow on terrain trafficability); and

(5) weather trafficability for air operations (used to represent the effects of wind speed and direction on air operations).

To determine the effects of precipitation on movement of vehicles, it is necessary to know the type of terrain over which movement is being conducted. Rain may interact with most types of terrain to produce mud which impedes movement, but rain interacting with some terrain types may have a positive effect on mobility.[1] To reflect this combined effect of weather and terrain on ground trafficability, an environmental trafficability index is determined within the model as a function of the current weather trafficability index for ground movement and the terrain trafficability index. Six levels of environmental trafficability are represented. Similarly, an environmental visibility index is computed within the model as a function of the current weather visibility index for ground-to-ground operations and the terrain visibility index. Six levels of environmental visibility are available and are used by the model when the combined effects of terrain line of sight and

[1]Movement over desert terrain may be aided by infrequent precipitation which packs the sand.

weather on ground visibility are needed.

2.1.7 Missions and Activities. Maneuver forces in VECTOR-2 are assigned missions and carry these missions out as activities. At the sector level, missions are assigned from the following list:[1]

(1) advance;

(2) hold;

(3) hold, delay if attacked;

(4) hold, withdraw if attacked; and

(5) withdraw.

Subordinate maneuver units within a sector (at any level down to front-line battalion task forces) are assigned missions from the following list:[1]

(1) advance;

(2) hold;

(3) hold and delay if attacked;

(4) hold and withdraw if attacked; and

(5) withdraw to a fixed location.

In carrying out their missions, front-line units engage in various fire and maneuver activities. They may move forward or backward within the combat arena in which they are operating, and they may engage in combat at a defensible position, combat between defensible positions (while the defender is moving to the next position to the rear), combat at a river, combat in an urban area, or combat at a user-defined terrain feature. Such combat might be of the nature of an assault against a defender, or might be associated with an advance against a delaying action or a pursuit against a withdrawal.

[1] These mission statements can (and it is expected will) be expanded to include more specific time and terrain objectives, i.e., "Hold your current position for ten hours, however if attacked, delay the enemy force for two hours while moving back to the next defensible position".

Fixed-wing tactical aircraft may be assigned the missions of combat air support, escort, intercept, or interdiction. Aircraft assigned to the interdiction mission are allocated to engage acquired targets, including committed reserve units, uncommitted reserve units, command posts, airbases, supply depots, field artillery batteries, air defense sites, or target acquisition resources. In carrying out these missions, the aircraft may become involved in air-to-air combat.

Attack helicopters may be assigned a fire support role or may participate as a maneuver-unit weapon in front-line combat. Those helicopters performing fire support missions can be assigned to attack maneuver-unit elements, committed or uncommitted reserve units, command posts, airbases, depots, target acquisition resources, field artillery batteries or air defense sites. Those participating in a maneuver unit engagement perform the same activities as the maneuver unit which they are supporting.

Field artillery weapons may conduct pre-engagement fires (including preparatory fire and counter-preparatory fire) against maneuver units, opposing field artillery, and air defense artillery. They may participate in final protective fires against attacking maneuver units,[1] and may conduct disengagement fires against front-line maneuver units. They may also be allocated to fire at acquired targets, including front-line maneuver units, committed reserve units, uncommitted reserve units, command posts, depots, target acquisition resources, artillery batteries, air defense sites, or airbases.

Air defense artillery may engage attack helicopters and fixed-wing aircraft which are en route to or from ground targets or which are attacking the air defense sites or targets near the sites.

[1] Mortars and machine guns also participate in final protective fires.

2.1.8 Intelligence. The commander's perception of the enemy and the area of operations is represented in VECTOR-2 by a set of state variables describing the current status of knowledge about the terrain, future weather conditions, potential targets, and the enemy's order of battle. Weather intelligence is in the form of five-day forecasts by both Red and Blue of future weather trafficability and visibility indices. Target intelligence acquires targets, against which fire support may be allocated. Kinds of targets which may be acquired include front-line maneuver units, field artillery batteries, air defense artillery sites, command posts, logistical targets, uncommitted maneuver unit reserves, committed maneuver unit reserves in transit, penetrating aircraft groups, aircraft and helicopter bases, and target acquisition resources. Order-of-battle intelligence consists of current estimates of the strengths of enemy maneuver units by coordinates (both front line and reserve), and numbers of other resource groups by zone.

2.2 Representation of Processes in VECTOR-2. Six types of processes modeled in VECTOR-2 cause dynamic change in values of the state variables. These types are as follows:

(1) Firepower processes are processes in which the firepower of one of the opposing sides causes damage to elements or supplies of the other side.

(2) Command and control processes include the processes of command decision making in response to situations on the battlefield.

(3) Intelligence and target acquisition processes collect information about terrain, future weather conditions, potential targets, and the enemy order of battle for use in fire support allocation and command and control processes.

(4) Communications processes relay information between intelligence, command, and combat elements on the battlefield and include the time delays inherent in

such information transmission.

(5) Logistics processes include the consumption of supply items by force elements in VECTOR-2, and the resupply of weapons, personnel, and supplies to combat units.

(6) Movement processes include the movement of forces on the battlefield as part of the gaining or losing of ground by front-line forces, the commitment of reserves, the retirement of front-line units, and the movement of air flights during missions.

The following sections describe these processes and list their outputs.

2.2.1 Firepower Processes. VECTOR-2's firepower process models describe different mechanisms of delivering firepower and the effects of these firepower processes on force composition values, supply levels, and the inventories of other targets. The specific firepower processes represented in VECTOR-2 can be grouped into four general categories:

(1) Ground-to-ground firepower processes include maneuver unit activities such as an assault against a hasty defense, an advance against a delay, a pursuit against a withdrawal, a river crossing, or urban warfare; also included are field artillery effects against front-line maneuver units, reserves, air defense artillery, field artillery, etc.; and the effects of minefields against maneuver units.

(2) Air-to-ground firepower processes include attack helicopters and fixed-wing aircraft attacks on maneuver units and other targets such as command posts, supply depots, reserves, airbases, attack helicopter bases, field artillery, air defense artillery, etc.

(3) Ground-to-air firepower processes consist of the effects of air defense artillery on attack helicopters and fixed-wing aircraft attacking ground targets.

(4) Air-to-air firepower processes include the interactions of interceptors versus escorts and interceptors versus attacking aircraft.

In constructing models of these processes, the relationship of fires at a target and fires by that target has required the construction of "duel" models or sets of many of these processes. included among these models are models of the effects of the fires of opposing maneuver units on each other; models of the effects of counterbattery fire; models of the effects of the fires of interceptor and escort aircraft and of interceptor and attack aircraft on one another; models of the effects of attack helicopter fires on maneuver units and of the fires by maneuver units and associated air defense weapons on attack helicopters; and models of the effects of the fires of attack aircraft flying air defense suppression missions on their targets and the fires of these air defense weapons on the attacking aircraft.

In all these areas, whether a duel model is involved or not, the models used in VECTOR-2 have been built from detailed models of the firing behavior and physical damage processes involved. In some cases, these detailed models are themselves used in VECTOR-2 and in others, VECTOR-2 uses a summary model for which data can be generated from the available detailed models of the process. Thus, inputs to each of these models are either directly measurable quantities or can be estimated from systems engineering models or more detailed combat process models.

The air-to-air firepower process model describes the interactions of the duel involving attack aircraft and their escorts versus opposing interceptors. Outputs of this submodel include the number of surviving aircraft, by type and the number of aircraft aborting their mission, by type.

The ground-to-air firepower process models describe the interactions of air defense artillery against fixed-wing aircraft and attack helicopters flying missions to attack ground targets

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(as a function of aircraft type and flight path),[1] and the effects of ground maneuver forces and associated air defence weapons engaging attack helicopters. The first of these process models considers the effects on the aircraft during the flight to its target while in its target's area, and during the return flight. Models of maneuver force engagements generate the number of attack helicopters attrited, when helicopters are involved in such engagements.

The air-to-ground firepower process models separately describe the effects of aircraft or attack helicopters against maneuver units at the FEBA and aircraft or attack helicopters against other targets such as reserves, supplies, sheltered and unsheltered aircraft at airbases, etc. The models describing the firepower processes against maneuver forces at the FEBA generate surviving numbers of weapon systems (by type) in the maneuver force, while the models describing firepower effects against other ground targets generate the remaining number of elements in the target.

The ground-to-ground firepower processes include maneuver unit combat; artillery against maneuver forces at the FEBA; artillery against other targets (other artillery, etc.); and minefield effects against maneuver forces. The models describing artillery effects against maneuver forces at the FEBA generate estimates for the expected number of surviving elements in a maneuver force (by weapon system type and personnel in that unit), and the model describing artillery effects against other targets generates estimates of the expected number of target elements and associated personnel surviving. The minefield effects model determines the movement delays and expected number of surviving elements in a

[1] Including the effects of air defense artillery engaged in a duel with attacking aircraft.

maneuver force for personnel and each weapon system type.

The effects of firepower (and other) processes in combat activities between maneuver forces at the FEBA are computed internally using VRI's differential models of combat. These models describe the dynamics of small unit firefights at the FEBA. The models explicitly consider different weapon system types on each side (tanks, antitank systems, mounted infantry, etc.), characteristics of these weapon systems (their firing rates, accuracy of fire, projectile flight times, lethality of the projectile), vulnerability of the target by type, firing doctrine of the weapon system (single rounds, burst fire, volley), probabilistic acquisition of targets in the firefight, allocation priorities of weapon systems to targets, maneuver capability of the weapon systems, and the effects of terrain line of sight on acquisition and fire capabilities. The model computes the attrition of weapon systems by type and personnel for the opposing units as successive ranges as the units maneuver during the engagement. Based on user-supplied tactical decision rules, the force may break off the combat activity or may call for fire support or both. Output of this model is a complete description of the surviving weapons systems by type and personnel at the end of the combat activity.

2.2.2 Command and Control Processes. The command and control process models in VECTOR-2 represent tactical decision making at all command levels from theater down to battalion. These models provide a structure within which the user may input appropriate "tactical decision rules" that describe the behavioral and decision processes which are an integral part of any military activity. A tactical decision rule is a rule that associates a decision (a choice among alternative courses of action) with different sets of values of the state variables of the model. In VECTOR-2, these rules take the form of user-defined subprograms in the FORTRAN computer language. The user has complete flexibility to specify the state variables that are considered in the rule and and the functional form of the rule. Essentially, the user can

set the value of any state variables as a user-selected function of the values of any other state variables contained in the model.

At the theater level of command, rules which perform the following functions are input to the VECTOR-2 program:[1]

(1) assignment of missions to sectors;
(2) assignment of maneuver units to sectors;
(3) assignment of non-organic units[2] to sectors;
(4) assignment of fixed-wing aircraft to bases;
(5) assignment of supplies and replacement weapons and sectors;
(6) reassignment of maneuver units from one sector to another; and
(7) assignment of missions to fixed-wing aircraft.

At the sector level, the following functions are performed by tactical decision rules:

(1) assignment of missions to subordinate units;
(2) assignment of non-organic field artillery to divisions or separate brigades;[3]
(3) assignment of non-organic attack helicopters from corps to divisions or separate brigades;[3]
(4) assignment of supplies and replacement weapons and personnel from sector to subordinate units;
(5) assignment of missions to the creation of task forces;
(6) assignment of attack helicopters from division to maneuver units;
(7) allocation of combat air support to front-line maneuver units; and
(8) assignment of minefields to combat arenas.

[1]A base set of tactical decision rules developed by VRI and military staffs over the course of a number of previous studies is available to users of VECTOR-2.

[2]Non-organic units are those air defence, attack helicopter, and field artillery forces not a part of US corps, divisions or separate brigades or corresponding foreign units.

[3]Or to corresponding foreign units.

At the level of the battalion task force, three functions are performed by tactical decision rules:

(1) situation assessment (possibly resulting in a change in activity by the task force or generation of a request for support from a higher headquarters);

(2) response from higher headquarters to requests for support; and

(3) determination of target priorities and allocation of targets to fire support resources.

The VECTOR-2 command and control process models include all of these user-provided rules as well as a representation of the interactions of the rules with each other through the command hierarchy and with other modeled processes.

2.2.3 Intelligence and Target Acquisition Processes. VECTOR-2's representation of the processes of intelligence and target acquisition includes models representing terrain intelligence, weather intelligence, and acquisition of ground and air targets for fire support, and the collection of air and ground order-of-battle intelligence. Weather intelligence is represented as five-day forecasts which are input by the user for each day of simulated combat. The model of the ground target acquisition process develops and maintains a list of the expected number of acquired targets by type of target, location of target, and type of target acquisition resource. The model of the air target acquisition process develops and maintains a list of the expected number of acquired air flights by location of the flight and type of acquisition resource. These lists are used by tactical decision rules to allocate fire support to the acquired targets. The order-of-battle intelligence process model utilizes information obtained from intelligence resources to produce estimates of the number of resource groups by type in a given zone, the estimated strength of maneuver units, both front line and reserve, at a given point in time, and estimates of the number of aircraft operating in each sector. These estimates are provided as input to tactical decision rules.

2.2.4 Communications Processes. The communications process model in VECTOR-2 transmits intelligence and command and control decisions throughout the command hierarchy. The effects of the communications processes are represented by the expected value of delays incurred in transmitting messages from their origins to their destinations. These communications lags affect the combat process by resulting in delays in initiating and implementing decisions.

2.2.5 Logistics Processes. Logistics processes in VECTOR-2 include the consumption of supplies represented in the model and the replacement of personnel and material that are destroyed or consumed during the campaign. Consumption of supplies occurs as the result of combat activity and the passage of time. Consumption of ammunition during maneuver unit engagements is computed at each range step in the differential models of combat based on the expected number of rounds fired to achieve the expected attrition calculated. In other combat activities, expenditure of supplies is computed on the same basis as its associated firepower process model. For example, if the firepower model gives effects on a per-sortie basis, parallel data items give ammunition and POL expended per sortie. Consumption of supplies based simply on the passage of time is intended to simulate consumption resulting from activities that are not explicitly included in the model. The consumption process models used in VECTOR-2 are generally linear forms representing consumption as a sum of terms, each of which is the product of an input consumption rate and a state variable (generally measuring or serving as a proxy for the amount of some activity). In addition to these consumption models, reduction in supply levels may occur as the result of destruction by firepower. This destruction is considered as part of the firepower process models.

As weapon systems, target acquisition resources, ammunition, POL, other supplies, and personnel are attrited or consumed, they are replaced in accordance with user-supplied tactical rules. The arrival to the theater or to individual sectors of these new wea-

pons, personnel, and supplies (as well as entire new units) is controlled with input generated by the user. Tactical decision rules then allocate these arrivals first to sectors (in the case of arrivals to the theater), and then to subordinate units within sectors, as required.

2.2.6 Movement Processes. VECTOR-2 explicitly represents air flight and maneuver unit movement. The initiation of movement is governed by tactical decision rules (possibly delayed by communications and decision lags). Given such a decision for a front-line or reserve maneuver unit, close combat and non-combat movement rates (assault, delay, unimpeded, etc.) which are a function of unit composition are used to represent the travel of the unit from its origin to its destination. Similar rates are used to represent the movement of flights of attack or interceptor aircraft from their airbase or loitering position to their target and back at the end of the mision.

2.3 Structure of VECTOR-2. The process models outlined in the previous section are applied repeatedly during a simulated campaign in VECTOR-2 to produce a history of state variable values through the engagement. These process models are applied to several levels of the command hierarchy at appropriate points during each model time period throughout the campaign. Depending on the specific process and command level represented, the size of the time steps within a model time period varies in order to allow for adequate representation of the relative timing of events during a model time period. In addition, events are sequenced within a time step to allow for further timing considerations.

2.4 VECTOR-2 Inputs and Outputs. VECTOR-2 requires as input:

(1) data which describe the quantitative performance capabilities of the forces, weapon systems, and other resources in the dynamic processes discussed in section 2.2

(2) initial force and supply inventory data and a schedule of unit, weapon, personnel, and supply arrivals;

(3) data describing the environment (terrain and weather) in which these forces operate; and
(4) tactical decision rules.

The total trajectory of most state variables during a campaign are stored for use by a post-processor which can provide aggregated statistics on detailed information in the form of tables, graphs, etc. for analysis. Representative model outputs include:

(1) model time period and cumulative weapon system losses by weapon type;
(2) model time period and cumulative casualties;
(3) supply totals by type of supply;
(4) total weapon system survivors by weapon type;
(5) weather conditions;
(6) a map of the battlefield including zones and their compositions;
(7) acquired targets by type;
(8) numbers of sorties flown on each mission by each aircraft type;
(9) the following information for each front-line task force;
  (a) number of weapon systems (by type), number of personnel, and supply levels;
  (b) minefields deployed;
  (c) FEBA position;
  (d) distance the force moved during the current time period;
  (e) current activity; and
  (f) reserve units employed;
(10) attributions of casualties (by location) and weapon system losses (by type) to the following attrition agents:
  (a) maneuver unit weapons (and ADA in the case of helicopter kills);

(b) fixed-wing aircraft (and ADA in the case of aircraft losses);

(c) field artillery;

(d) attack helicopters; and

(11) unit arrivals pending to the theater and to each sector.

DISCUSSION

Thompson: What sort of validation work have you done on this model? What combat situations have you prepared and input to it?

Bonder: We have not performed a real verification in the scientific sense. We haven't collected war data to do this. Although there is a set of data available now if people want to do this (i.e., the Mideast War), nobody is interested in verifying it for some reason. Let me tell you what we have done. The maneuver unit combat activities that are in VECTOR-2 are clearly not large scale Monte Carlo simulations. They are analytic formulations of the engagements. These have been compared with high resolution Monte Carlo simulations of the maneuver unit combats and have been shown to produce very similar results. All I am saying is that the analytic models were compared to models that the military seems to think are realistic. Both models could be wrong. I am not trying to make the point that we have verified it. We have compared with models that the military seems to think describe their processes. We have not conducted a verification study, and nobody I know has. We would like to and data exists to do it.

Question: Do you have the Air Force command and control simulation in there?

Bonder: The only command and control elements in the model are for the maneuver unit command structure. We play a lot of Air Force decisions, but aircraft come into the theater by unit name and then they get deployed to airbases where they lose their identities as headquarters.

REMARKS ON THE PRESENTATION GIVEN BY SETH BONDER

by J. R. THOMPSON
Rice University

In response to my question as to the capabilities of the interactive mode of VECTOR II, Dr. Bonder informs me that there is no such mode. Thus, the model may not be used as a simulator for command training. This is, in my view, a serious defect.

In response to my question as to the validation of VECTOR II by case studies on real world theatre combat data, Dr. Bonder states that no such validation has been contemplated, although "validation" against earlier combat models indicates some consistency with earlier generation models. I find the absence of validation with historical combat data to be a serious defect.

Of course, in fairness to Dr. Bonder and VECTOR, I should mention that I had anticipated his answers to my questions, since both of the aforementioned defects are present in the DOD large scale models built at a cost of millions over the last dozen years. It has become traditional to leave real time man-made decisions out of computer combat models. It has also become traditional to "validate" (n+1)th generation models by comparing them with (n)th generation models instead of resorting to historical data. If the present models have much relation to reality, then I would say that an event of probability measure nearly zero has occurred. To keep financing generation after generation of models of increasing cost and complexity without ever a reasonable attempt at validation is simply throwing good money after bad. More serious than the wastage of a few hundred megabucks is the fact that these models are used as partial justifiers of the purchase of billions of dollars of military hardware. Of course, since these combat models are not constrained by consistency with real world data, they do have the "practical" advantage that one

can juggle the input parameters around until a predetermined weapons policy is supported.

Finally, I should like to make a general comment about some prior impressions reinforced during the conference. The systems analyst and his computer have replaced the court astrologer and his astrolabe as pseudo-scientific aids to the military. On balance, there is much to be said for the astrologer. He wrote his reports in high literary Latin and had a lower overhead rate than that of his modern counterpart.

That systems analysis should hold such sway in the DOD is both unfortunate and unnecessary. The assumption that management science techniques with slight or no modification are applicable to military situations is not supported by experience--including the Vietnam War. The structure of military decision theory should begin with military history and take its axioms form that body of knowledge. I would suggest that high priority be given to the creation and development of a science of quantitative military science (tactometrics). Such a science would undoubtedly have some points of convergence with existing mathematical sciences (operations research, statistics, computer science, etc.). But it should be a science sui generis. National defense is sufficiently important that that DOD should be willing to undertake the admittedly difficult task of creating a new science tailored for military purposes. To continue the present policy of assuming that a modelling approach which is good for General Motors is good for the DOD would be both expensive and risky.

STOCHASTIC COMBAT MODELING - LANCHESTER'S FIRST LAW

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Abstract. In this paper, a stochastic version of Lanchester's Linear Law is presented. With this extended model, the elimination rates and the operational rate losses are treated as random variables. Liouville's theorem from the study of random differential equations is utilized to find the joint probability density function of the solution process of the stochastic system. Assuming that the a priori joint probability distribution of the random initial conditions and the random rate constants is multivariable normal, the expected values and the standard deviations of the solution are derived. Their trajectories are plotted and compared to their deterministic counterparts. An application of the system is given for heterogeneous forces.

1.0 Introduction. In this paper we shall modify Lanchester's First Law of Combat using a *stochastic analysis* as applied to the rates of elimination between the enemy forces.

The significance of the concentration of troops under modern combat conditions were singled out by F. W. Lanchester in 1916, [4], and is referred to today as Lanchester's Law. In mathematical terms, this law states that the strength of a military force is proportional to the average effectiveness per unit times the square of the number of units in the conflict. That is, the strength, S, of a military force is given by

$$S = kMU^2 \tag{1.1}$$

where

(i) M is the average effectiveness per unit, and

(ii) U is the number of units employed.

This fundamental law is used to analyze the combat between two sides, Blue and Red. We shall assume that the two forces are homogeneous, and that the number of units of the Blue and Red

forces at time t is m(t) and n(t), respectively. Furthermore, each side does not receive reinforcements after the battle begins.

Lanchester used law (1.1) to state two laws governing the attrition of the Blue and Red forces. These are the

Linear Law

$$\begin{cases} \dfrac{dm}{dt} = cn \\ \dfrac{dn}{dt} = c'm, \end{cases} \tag{1.2}$$

and the

Quadratic Law

$$\begin{cases} \dfrac{dm}{dt} = - dmn \\ \dfrac{dn}{dt} = =d'mn, \end{cases} \tag{1.3}$$

where c and d (c' and d') are the elimination rates that a Red (Blue) unit destroys a Blue (Red) unit per unit time. Law (1.2) applies to combat at close quarters. (The Quadratic Law is valid for a long range combat situation.)

We shall be concerned with the formulation of a stochastic model analogue of law (1.2) for homogeneous forces.

It seems appropriate here to give a brief summary of previous studies on this subject and the reasoning which leads to our analysis below.

Thrall, [7], concludes that the number, say, of Red units destroyed during the interval of time [0,T] is a random variable with an approximately normal distribution. The variance is disregarded and the random variable is replaced by its mean, μ, yielding a deterministic approximation:

$$\frac{dn}{dt} \cong \frac{\mu}{T} \tag{1.4}$$

The solution n(t) is a mean representation and should be compared to the expected value, $E\{N(t)\}$, in order to best analyze the randomness inherent in this real-life situation. Moreover, operational loss rates due to causes other than enemy fire are disregarded in this model.

Stubbs, et. al. [5], consider these operational rate losses, but treat them as constants with time. The effectiveness of any Red or Blue unit is determined by calculating the number of enemy units that it can destroy per unit time. They may be considered to be the random variables

$K_{BR}(K_{RB})$: rate at which a Blue (Red) unit destroys a Red (Blue) unit per unit time.

The operational rate losses are denoted by

$k_{E_B}(k_{E_R})$: operational rate loss of Blue (Red) units per unit time.

Utilizing the expected values of K_{BR} and K_{RB}, they obtained the model

$$\begin{cases} \dfrac{dn}{dt} = - E[K_{BR}]m - k_{E_R} n \\ \dfrac{dm}{dt} = - E[K_{RB}]n - k_{E_B} m. \end{cases} \tag{1.5}$$

The trajectories for n(t) and m(t) will be based on average values for K_{BR} and K_{RB} and therefore, the model (1.5) is deterministic.

Engel, [2], treats the rates k_{BR} and k_{RB} as constants.

Brackney, [1], considers the model

$$\begin{cases} \dfrac{dn}{dt} = - P_m r_m m \\ \dfrac{dm}{dt} = - P_n r_n n, \end{cases} \tag{1.6}$$

where

(i) $r_m(r_n)$ is the rate at which a Blue (Red) unit destroys a Red (Blue) unit,

and

(ii) $P_m(P_n)$ is the probability that a Blue (Red) unit destroys an individual Red (Blue) unit.

This model omits the operational rate losses and treats the effectiveness (destruction) rates by a priori probabilities, P_m and P_n, respectively.

We shall extend the Lanchester combat model in the

following way:

$$\dot{M}(t) = -K_{RB}n - K_{E_B}m$$

$$\dot{N}(t) = -K_{BR}m - K_{E_R}n, \qquad (1.7)$$

with random or deterministic initial conditions

$$M(0) = M_0,$$

and

$$N(0) = N_0, \qquad (1.8)$$

where

(i) $K_{BR}(K_{RB})$ is the random rate per unit time that a Blue (Red unit destroys a Red (Blue) unit,

(ii) $K_{E_B}(K_{E_R})$ is the random rate of non-combat elimination of Blues (Reds) per unit time.

(iii) $\dot{M}(t)(\dot{N}(t)0$ is the mean square derivative of $\dot{N}(t)$ (N(t)) at t. We remark here that the random coefficients are time independent.

Figure 1 below gives a schematic diagram of the model (1.7) - (1.8).

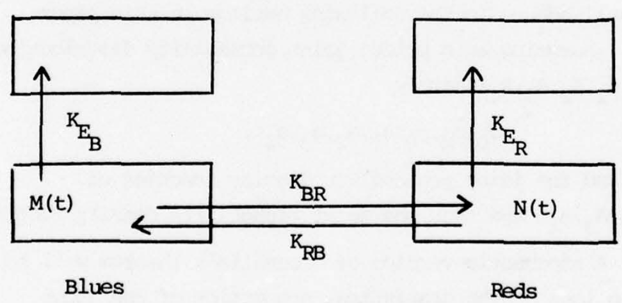


FIGURE 1

For simplicity in notation, let

$$K_{RB} = A_1,$$

$$K_{E_B} = A_2,$$

$$K_{BR} = A_3,$$

and

$$K_{E_R} = A_4.$$

System (1.7)-(1.8) can be written as

$$\dot{\underline{U}} = \begin{bmatrix} \dot{M} \\ \dot{N} \end{bmatrix} = \begin{bmatrix} -A_2 & -A_1 \\ -A_3 & -A_4 \end{bmatrix} \underline{U} \tag{1.9}$$

with

$$\underline{C} = \begin{bmatrix} M_0 \\ N_0 \end{bmatrix}, \tag{1.10}$$

where

$$\underline{U}(t) = \begin{bmatrix} M(t) \\ N(t) \end{bmatrix}.$$

We shall adhere to the following outline in this paper:

(i) Assuming an a priori joint probability distribution of $(M_0, N_0, A_1, A_2, A_3, A_4)$ namely

$$f_0(m_0, n_0, a_1, a_2, a_3, a_4),$$

we shall find the joint probability density function of $(M, N, A_1, A_2, A_3, A_4)$ and thus the joint probability density function of (M,N). A stochastic version of Liouville's theorem will be employed to look at the statistical properties of the above model.

(ii) The trajectories of $E[M(t)]$ and $E[N(t)]$ will be compared to the deterministic solutions $m(t)$ and $n(t)$ of system (1.9) and (1.10). Also the trajectories of $\sigma_{M(t)}$ and $\sigma_{N(t)}$ and

their deterministic counterparts will be compared under the assumption that $(M_0, N_0, A_1, A_2, A_3, A_4)$ is distributed as multivariate normal.

(iii) We shall explain how the theory for homogeneous forces can be adapted to heterogeneous forces.

Knowledge of the joint probability density function of (M,N),

$$f(\underline{u};t) = f(m,n;t), \tag{1.11}$$

has practical significance. One might wish to determine the probability that the force levels of the combatants are within certain bounds at time t. This is accomplished by evaluating

$$\int_R f(\underline{u};t)\,d\underline{u},$$

where R is the appropriate region by the given bounds and $\int_R$ represents the necessary multiple integral.

2.0 Determination of Some Statistical Properties of the Random Solution of System (1.9)-(1.10). We shall begin this problem by stating some necessary notation to be used throughout this paper. The vector differential equation (1.9) can be expressed as

$$\dot{\underline{U}}(t) = \underline{h}(\underline{U}(t), \underline{A}; t) \tag{2.1}$$

with random initial conditions

$$C = U(0), \tag{2.2}$$

with random coefficients

$$\underline{A} = (A_1, A_2, A_3, A_4)^T. \tag{2.3}$$

The joint probability density function of $\underline{C}$ and $\underline{A}$ is

$$f_0(\underline{c}, \underline{a}). \tag{2.4}$$

The random solution of equation (1.9) has the form

$$\begin{aligned} \underline{U}(t) &= \underline{g}(\underline{C}, \underline{A}; t) \\ &= \begin{bmatrix} \underline{g_1}(\underline{C}, \underline{A}; t) \\ \underline{g_2}(\underline{C}, \underline{A}; t) \end{bmatrix}, \end{aligned} \tag{2.5}$$

where $\underline{g_1}$, $\underline{g_2}$ are functions of t with

$$\underline{C} = \begin{bmatrix} M_0 \\ \\ N_0 \end{bmatrix}$$

and

$$\underline{A} = (A_1, A_2, A_3, A_4)^T.$$

We shall now make use of the fundamental Liouville's theorem in the theory of dynamic systems. A proof of this theorem is given by Syski, [6]. An alternate proof of concept of characteristic functions is due to Kozin, [3] Theorem (2.1). Consider a vector differential equation (2.1)

$$\underline{U}(t) = \underline{h}(\underline{U}(t), \underline{A}; t)$$

with random coefficients, $\underline{A}$. The joint probability density function of $\underline{C}$ and $\underline{A}$ is

$$f_0(\underline{c}, \underline{a}).$$

Assume that the solution of equation (2.1),

$$\underline{U}(t),$$

exists in the mean square sense. Then the joint density function of $\underline{U}(t)$ and $\underline{A}$,

$$f(\underline{u}, \underline{a}; t) \tag{2.6}$$

satisfies the Liouville equation

$$\frac{\partial f}{\partial t}(\underline{u}, \underline{a}; t) + \sum_{j=1}^{n+m} \frac{\partial [fhj]}{\partial u_j} = 0, \tag{2.7}$$

where

(i) h_j and u_j are the j^{th} components of the vectors $\underline{h}$ and $\underline{u}$.

(ii) The dimensions of the vectors $\underline{u}$ and $\underline{a}$ are n and m, respectively. Formula (2.7) is useful particularly when the dimension of the Jacobian is large.

We thus see that the problem of determining the joint probability density function $f(\underline{u}, t; \underline{a})$ using the Liouville's theorem

is an initial value problem for first-order partial differential equations, the initial value being the joint probability density function of $\underline{C}$ and $\underline{A}$, $f_0(\underline{c},\underline{a})$.

The general solution of equation (2.7) is readily obtained by examining the associated Lagrange system

$$\frac{dt}{1} = -\frac{df}{f\nabla\cdot\underline{h}(\underline{u},\underline{a};t)} = \frac{du_1}{f_1} = \cdots = \frac{du_n}{f_n}, \tag{2.8}$$

where

(i) $\nabla\cdot\underline{h}$ is the divergence of the vector $\underline{h}$.

The first equality in equation (2.8) yields the solution, the joint probability density function of $\underline{U}$ and $\underline{A}$,

$$f(\underline{u},\underline{a};t) = f_0(\underline{c},\underline{a}) \exp \left\{ - \int_0^t \nabla\cdot\underline{h}[\underline{u} = \underline{g}(\underline{c},\underline{a};\tau), \underline{a};\tau]d\tau \right\} \Bigg|_{\underline{c} = \underline{g}^{-1}(\underline{u},\underline{a};\tau)}, \tag{2.9}$$

where

(i) $\underline{g}(\underline{C},\underline{A};t)$ is the explicit solution of $\underline{U}(t)$.

The joint probability density function $f(\underline{u};t)$ of (M,N) is obtained from equation (2.9) as

$$\begin{aligned} f(\underline{u};t) &= \int_R f(\underline{u},\underline{a};t)d\underline{a} \\ &= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(\underline{u},\underline{a};t)da_1 da_2 da_3 da_4. \end{aligned} \tag{2.10}$$

We shall now apply the above theory to the extended model (1.9)-(1.10), which is expressed as

$$\begin{aligned} \dot{\underline{U}}(t) &= \begin{bmatrix} -A_2M(t) - -A_1N(t) \\ \\ -A_3M(t) - -A_4N(t) \end{bmatrix} \\ &= \underline{h}(U(t),\underline{A};t), \end{aligned} \tag{2.11}$$

with

$$\underline{C} = (M_0, N_0)^T,$$

$$\underline{A} = (A_1, A_2, A_3, A_4)^T,$$

and

$$V \cdot \underline{h} = \begin{bmatrix} \frac{\partial}{\partial M} \\ \\ \frac{\partial}{\partial N} \end{bmatrix} \cdot \underline{h}$$

$$= - (A_1 + A_4). \tag{2.12}$$

We shall now solve equation (2.11) for

$$\underline{U}(t) = \underline{g}(\underline{C}, \underline{A}; t),$$

and use equation (2.9) to find the joint probability function of $\underline{U}(t)$ and $\underline{A}$, namely,

$$f(\underline{u}, \underline{a}; t) = f(m, n, a_1, a_2, a_3, a_4; t). \tag{2.13}$$

We assume a solution of equation (2.11) of the form

$$\underline{u}(t) = \begin{bmatrix} \alpha e^{\lambda t} \\ \\ \beta e^{\lambda t} \end{bmatrix}. \tag{2.14}$$

A non-trivial solution of equation (2.1) exists if and only if

$$\left| \lambda \begin{bmatrix} 1 & 0 \\ \\ 0 & 1 \end{bmatrix} - \begin{bmatrix} -a_2 & -a_1 \\ \\ -a_3 & -a_4 \end{bmatrix} \right| = 0. \tag{2.15}$$

The solutions for the eigenvalues in equation (2.15) are

$$\lambda_1 = \frac{-(a_2+a_4) + \sqrt{(a_2-a_4{}^2 + 4a_1a_3}}{2}, \tag{2.16}$$

and

$$\lambda_2 = \frac{-(a_2+a_4) - \sqrt{(a_2-a_4)^2 + 4a_1a_3}}{2}. \tag{2.17}$$

We note that since a_1, a_2, a_3, a_4 are all positive, we have

$$(a_2-a_4)^2 + 4a_1a_3 > 0.$$

The particular solution of equation (2.11) subject to the initial

condition

$$C = \begin{bmatrix} M_0 \\ \\ N_0 \end{bmatrix},$$

$$\underline{U}(t) = \frac{1}{(R_1-R_2)} \begin{bmatrix} R_1e^{\Lambda_1 t}-R_2e^{\Lambda_2 t} & -R_1R_2(e^{\Lambda_1 t}-e^{\Lambda_2 t}) \\ e^{\Lambda_1 t}-e^{\Lambda_2 t} & -R_2e^{\Lambda_1 t}+R_1e^{\Lambda_2 t} \end{bmatrix} C \tag{2.18}$$

where

$$R_1 = -\frac{A_1}{\Lambda_1+A_2} \tag{2.19}$$

and

$$R_2 = -\frac{A_1}{\Lambda_2+A_2}$$

if we let

$$B = \begin{bmatrix} R_1e^{\Lambda_1 t}-R_2e^{\Lambda_2 t} & -R_1R_2(e^{\Lambda_1 t}-e^{\Lambda_2 t}) \\ e^{\Lambda_1 t}-e^{\Lambda_2 t} & -R_2e^{\Lambda_1 t}+R_1e^{\Lambda_2 t} \end{bmatrix},$$

equation (2.18) takes the form

$$\begin{aligned} \underline{U}(t) &= \underline{g}(\underline{C},\underline{A};t) \\ &= B\underline{C}, \end{aligned} \tag{2.20}$$

which gives us

$$\underline{C} = (R_1-R_2)B^{-1}\underline{U}(t). \tag{2.21}$$

Furthermore, we can easily obtain

$$B^{-1} = \frac{1}{(R_1-R_2)^2e^{(\Lambda_1+\Lambda_2)t}} \begin{bmatrix} R_2e^{\Lambda_1 t}+R_2e^{\Lambda_2 t} & R_1R_2(e^{\Lambda_1 t}-e^{\Lambda_2 t}) \\ e^{\Lambda_2 t}-e^{\Lambda_1 t} & R_1e^{(\Lambda_1 t+\Lambda_2)t} \end{bmatrix} \tag{2.22}$$

Substituting the expression for B^{-1} as given by equation (2.22) into equation (2.21) we obtain

$$C = \begin{bmatrix} M_0 \\ \\ N_0 \end{bmatrix}$$

$$\frac{1}{(R_1-R_2)} \begin{bmatrix} -R_2 e^{-\Lambda_2 t} + R_1 e^{\Lambda_1 t} & R_1 R_2 (e^{-\Lambda_2 t} - e^{-\Lambda_1 t}) \\ \\ e^{-\Lambda_1 t} - e^{-\Lambda_2 t} & R_1 e^{-\Lambda_2 t} - R_2 e^{-\Lambda_1 t} \end{bmatrix} \underline{U}(t). \tag{2.23}$$

From equation (2.9), the joint probability density function of $(M(t), N(t), A_1, A_2, A_2, A_4)$ is

$$f(m,n,a_1,a_2,a_3,a_4;t) = f_0(m_0,n_0;a_1,a_2,a_3,a_4) \cdot \exp\left\{ -\int_0^t \nabla\cdot\underline{h}d\tau \right\} \tag{2.24}$$

where

$$\begin{bmatrix} m_0 \\ \\ n_0 \end{bmatrix} = \underline{g}^{-1}\left(\begin{bmatrix} m \\ \\ n \end{bmatrix}, A;t \right) ,$$

as given by equation (2.23).

From equation (2.12) we obtain

$$\int_0^t \nabla\cdot h d\tau = -\int_0^t -(a_2+a_4)d\tau = (a_2+a_4)t. \tag{2.25}$$

Hence, substituting the expression for $\underline{C}$ given by equation (2.23) and the expression for $-\int_0^t \nabla\cdot\underline{h}d\tau$ from equation (2.25) into equation (2.24), we have

$$f(u,a;t) = f(m,n,a_1,a_2,a_3,a_4;t)$$

$$= \exp[(a_2+a_4)t]f_0\{\frac{1}{r_1-r_2}[(-r_2 e^{-\lambda_2 t} + r_1 e^{-\lambda_1 t})m$$

$$+ r_1 r_2(e^{-\lambda_2 t} - e^{-\lambda_1 t})n], \frac{1}{r_1 r_2}[e^{-\lambda_1 t} - e^{-\lambda_2 t}]m$$

$$+ (r_1 e^{-\lambda_2 t} - r_2 e^{-\lambda_1 t})n],\ a_1, a_2, a_3, a_4\} \qquad (2.26)$$

The joint density function $f(\underline{u};t)$ is obtained from equation (2.26) by integration with respect to $\underline{a}$, that is,

$$f(\underline{u};t) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(\underline{u},\underline{a};t)\,da_1 da_2 da_3 da_4,$$

from equation equation (2.10)

The r^{th} moment, $E\{\underline{U}^r(t)\}$, of the solution process $\underline{U}(t)$ can be found from the formula

$$E\{U^r(r)\} = \int_{-\infty}^{\infty} \underline{u}^r(t) f(\underline{u};t)\,d\underline{u}.$$

However, to vary our approach, we shall calculate the r^{th} moments of $M(t)$ and $N(t)$ by the formulas

$$E\{M^r(t)\} = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} g_1^r(\underline{c},\underline{a};t) f_0(\underline{c},\underline{a})\,d\underline{c}d\underline{a}, \qquad (2.27)$$

and

$$E\{N^r(t)\} = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} g_2^r(\underline{c},\underline{a};t) f_0(\underline{c},\underline{a})\,d\underline{c}d\underline{a}, \qquad (2.28)$$

where $f_0(\underline{c},\underline{a})$ is the joint density function of the random variables $\underline{C}$ and A.

In order to make the notation more standard, we denote the random variables M_0, N_0, A_1, A_2, A_3, and A_4 by

$$X_1 = M_0,$$
$$X_2 = N_0,$$
$$X_3 = A_1,$$
$$X_4 = A_2,$$
$$X_5 = A_3,$$
$$X_6 = A_4,$$

We shall study the first and second moments of the solution process for $\underline{U}(t)$ for several cases.

Case 1: $X_1 \equiv x_1$, $X_2 \equiv x_2$ with probability one and (X_3,X_4,X_5,X_6) is distributed as truncated multivariate normal. For this case, let

$$X = (X_3,X_4,X_5,X_6)^T, \tag{2.29}$$

and

$$\mu = (\mu_3,\mu_4,\mu_5,\mu_6)^T, \tag{2.30}$$

where

$$\mu_i = E\{X_i\}, \qquad i = 3,4,5,6$$

The joint probability density function of (X_3,X_4,X_5,X_6) is given by

$$f_0(X;P,\mu) \begin{cases} = \dfrac{K\sqrt{P}}{(2\pi)^2} e^{-\frac{1}{2}(X-\mu)^T P(X-\mu)}, & x_3,x_4,x_5,x_6 > 0 \\ 0, \text{ elsewhere}, & \end{cases} \tag{2.31}$$

where

(i) K is a truncation factor,

(ii) $P = C^{-1}$,

with C given by

$$C = \begin{bmatrix} \sigma_{33} & \sigma_{34} & \sigma_{35} & \sigma_{36} \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \sigma_{63} & \cdot & \cdot & \sigma_{66} \end{bmatrix}$$

where

$$\sigma_{ij} = E\{[X_i-\mu_i][X_j-\mu_j]\}$$
$$= \sigma_{ji}, \qquad i,j = 3,4,5,6.$$

Using equations (2.18), (2.27), (2.28) and (2.31) we obtain

$$E\{M(t)\} = K\int_0^\infty \int_0^\infty \int_0^\infty \int_0^\infty \frac{1}{(r_1-r_2)}\left[\left(r_1 e^{\lambda_1 t} - r_2 e^{\lambda_2 t}\right) x_1\right.$$

$$+\left(-r_1r_2e^{\lambda_1 t}+r_1r_2e^{\lambda_2 t}\right)x_2\Bigg]\ f_0(X;P,\mu)\,dx_3dx_4dx_5dx_6, \tag{2.32}$$

$$E\{N(t)\} = K\int_0^{\infty}\int_0^{\infty}\int_0^{\infty}\int_0^{\infty}\frac{1}{(r_1-r_2)}\Bigg[\left(e^{\lambda_1 t}-e^{\lambda_2 t}\right)x_1$$

$$+\left(-r_2e^{\lambda_1 t}+r_1e^{\lambda_2 t}\right)x_2\Bigg]\ f_0(X;P,\mu)\,dx_3dx_4dx_5dx_6, \tag{2.33}$$

$$E[M^2(t)] = K\int_0^{\infty}\int_0^{\infty}\int_0^{\infty}\int_0^{\infty}\Bigg\{\frac{1}{(r_1-r_2)}\Bigg[\left(r_1e^{\lambda_1 t}-r_2e^{\lambda_2 t}\right)x_1$$

$$+\left(-r_1r_2e^{\lambda_1 t}+r_1r_2e^{\lambda_2 t}\right)x_2\Bigg]\Bigg\}^2 f_0(X;P,\mu)\,dx_3dx_4dx_5dx_6, \tag{2.34}$$

and

$$E[N^2(t)] = K\int_0^{\infty}\int_0^{\infty}\int_0^{\infty}\int_0^{\infty} n^2(t)\,f_0(X;P,\mu)\,dx_3dx_4dx_5dx_6, \tag{2.35}$$

where n(t) is given by equation (2.18).

The standard deviations $\sigma_{M(t)}$ and $\sigma_{N(t)}$ are calculated from the formulas

$$\sigma_{M(t)} = \{E[M^2(t)] - E^2[M(t)]\}^{1/2}, \tag{2.36}$$

$$\sigma_{N(t)} = \{E[N^2(t)] - E^2[N(t)]\}^{1/2}. \tag{2.37}$$

Case 2: (X_1,X_2) distributed as bivariate normal and X_3,X_4,X_5,X_6 are constants, namely

$$X_3 = a,$$

$$X_4 = b,$$

$$X_5 = c,$$

and

$$X_6 = d.$$

For this case,

$$X = (X_1, X_2)^T,$$

$$\mu = (\mu_1, \mu_2)^T,$$

$$\sigma_{11}\ \sigma_{12}$$

$$\begin{bmatrix} C = \sigma_{11} & \sigma_{12} \\ \sigma_{21} & \sigma_{22} \end{bmatrix},$$

and

$$P = C^{-1}$$

The joint probability density function of the bivariate random variable (X_1, X_2) is

$$f_0(x_1, x_2; \mu_1, \mu_2, \sigma_1, \sigma_2) = \begin{cases} \dfrac{K}{2\pi\sigma_1\sigma_2\sqrt{1-\rho^2}} \exp\left\{ - \dfrac{1}{2(1-\rho^2)} \left[\left(\dfrac{x_1-\mu_1}{\sigma_1} \right)^2 \right.\right. \\ \left.\left. - 2\rho \left(\dfrac{x_1-\mu_1}{\sigma_1} \right) \left(\dfrac{x_2-\mu_2}{\sigma_1} \right) + \left(\dfrac{x_1-\mu_2}{\sigma_2} \right)^2 \right] \right\}, \\ 0 < x_1, x_2 < \infty,\ -1 < \rho < 1, \\ 0, \qquad \text{elsewhere,} \end{cases} \tag{2.38}$$

where K is a truncation factor.

From equation (2.19) defining r_1 and r_2, we have for this case

$$r_1 = - \frac{a}{\lambda_1 + b},$$

and

$$r_2 = - \frac{a}{\lambda_1 + b},$$

where λ_1 and λ_2 are given by equations (2.16) and (2.17). Thus we have

$$E[M(t)] = \int_0^\infty \int_0^\infty m(t) f_0(x_1, x_2) dx_1 dx_2, \tag{2.39}$$

$$E[N(t)] = \int_0^\infty \int_0^\infty n(t) f_0(x_1,x_2)\,dx_1 dx_2, \tag{2.40}$$

$$E[M^2(t)] = \int_0^\infty \int_0^\infty m^2(t) f_0(x_1,x_2)\,dx_1 dx_2, \tag{2.41}$$

$$E[N^2(t)] = \int_0^\infty \int_0^\infty n^2(t) f_0(x_1,x_2)\,dx_1 dx_2, \tag{2.42}$$

where

(i) $m(t)$ and $n(t)$ are given by equation (2.18)

(ii) $f_0(x_1,x_2)$ is given by equation (2.38)

The standard deviations $\sigma_{M(t)}$ and $\sigma_{N(t)}$ are calculated from formulas (2.36) and (2.37).

If $\rho = 1$, X_2 becomes linearly related to X_1, that is,

$$X_2 = rX_1 + s, \tag{2.43}$$

where

$$r = \frac{\sigma_1}{\sigma_2}$$

and

$$\begin{aligned} s &= \mu_2 - \frac{\sigma_1}{\sigma_2}\mu_1 \\ &= \mu_2 - r\mu_1 \end{aligned} \tag{2.44}$$

In this case, we need only the density function for X_1, namely

$$f_0(x_1) = \begin{cases} \dfrac{K_2}{\sqrt{2\pi}\,\sigma_1} \exp\left\{ -\dfrac{(x_1-\mu_1)^2}{2\sigma_1^{\,2}} \right\}, & x_1 \geq 0 \\ 0, & \text{elsewhere.} \end{cases} \tag{2.45}$$

From equation (2.18) we observe that both $M(t)$ and $N(t)$ are functions of $X_1 = M_0$ only, since the elimination rates are constants and $\rho = 1$. Thus, we can write

$$\begin{aligned} M(t) &= T(M_0) \\ &= T(X_1), \end{aligned} \tag{2.46}$$

and

$$\begin{aligned} N(t) &= V(M_0) \\ &= V(X_1). \end{aligned} \tag{2.47}$$

Hence, using equations (2.46) and (2.47) we have

$$E[M(t)] = \int_0^\infty T(x_1) f_0(x_1) dx_1,$$

$$E[N(t)] = \int_0^\infty V(x_1) f_0(x_1) dx_1,$$

$$E[M^2(t)] = \int_0^\infty T^2(x_1) f_0(x_1) dx_1,$$

and

$$E[N^2(t)] = \int_0^\infty V^2(x_1) f_0(x_1) dx_1.$$

As before, $\sigma_{M(t)}$ and $\sigma_{N(t)}$ are obtained from formulas (2.36) and (2.37).

Case 3: Lastly, we shall consider the case where $(X_1, X_2, X_3, X_4, X_5, X_6)$ are distributed as truncated multivariate normal. Here we have

$$X = (X_1, X_2, X_3, X_4, X_5, X_6)^T,$$

$$\mu = (\mu_1, \mu_2, \mu_3, \mu_4, \mu_5, \mu_6)^T,$$

and the joint probability density function of $(X_1, X_2, X_3, X_4, X_5, X_6)$ is

$$f_0(X;P,\mu) = \begin{cases} \dfrac{K_3\sqrt{|P|}}{(2\pi)^3} \exp\{\frac{1}{2}(X- \ )^T P(X-\mu)\}, \\ x_i > 0, \ i = 1,2,3,4,5,6, \\ 0, \qquad \text{elsewhere}, \end{cases} \tag{2.48}$$

where

(i) K_3 is the truncation factor;

(ii) $C = [\sigma_{ij}]$

$= [E\{(X_i-\mu_i)(X_j-\mu_j)\}]$

and

(iii) $P = C^{-1}$.

As in cases 1 and 2, we have

$$E[M(t)] = \int_0^\infty \int_0^\infty \int_0^\infty \int_0^\infty \int_0^\infty \int_0^\infty m(t) f_0(X;P,\mu) \cdot dx_1 dx_2 dx_3 dx_4 dx_5 dx_6,$$

$$E[N(t)] = \int_0^\infty \int_0^\infty \int_0^\infty \int_0^\infty \int_0^\infty \int_0^\infty n(t) f_0(X;P,\mu) \cdot dx_1 dx_2 dx_3 dx_4 dx_5 dx_6,$$

etc.

where $M(t)$, $N(t)$ are given by equation (2.18).

3.0 Example. In the following example we assumed that the elimination rates were constants, namely

$A_1 \equiv 1,$

$A_2 \equiv .1,$

$A_3 \equiv 1.1,$

and

$A_4 \equiv .1.$

The random initial values (M_0, N_0) were assumed to possess as a priori distribution which was truncated bivariate normal, having the parameters

$\mu_{M_0} = 100,$

$\mu_{N_0} = 70,$

$\sigma_{M_0} = 5,$

$$\sigma_{N_0} = \sqrt{45}.$$

In figure 3.1A, the random initial rates were assumed to be independent, that is $\rho = 0$. For figure 3.2A, we let $\rho = .5$.

Noticeable differences between the stochastic and deterministic trajectories occurred at time $t = .65$ units for both cases. The Red force was destroyed much more rapidly than the Blue force.

We remark that the erratic behavior of the trajectories for $E[N(t)]$ in both figures was due mainly to round-off error.

4.0 Heterogenous Forces. We shall now study the above theory as applied to heterogeneous forces.

The Blue and Red forces can be represented by the two vectors

$$\underline{m}(t) = (m_1(t), m_2(t), \ldots, m_p(t)),$$

and

$$\underline{n}(t) = (n_1(t), n_2(t), \ldots, n\ (t)),$$

where

(i) $m_i(t)$ is the number of the i^{th} homogeneous Blue force component remaining at time $t \geq 0$,

(ii) $n_j(t)$ is the number of the j^{th} homogeneous Red component remaining at time $t \geq 0$.

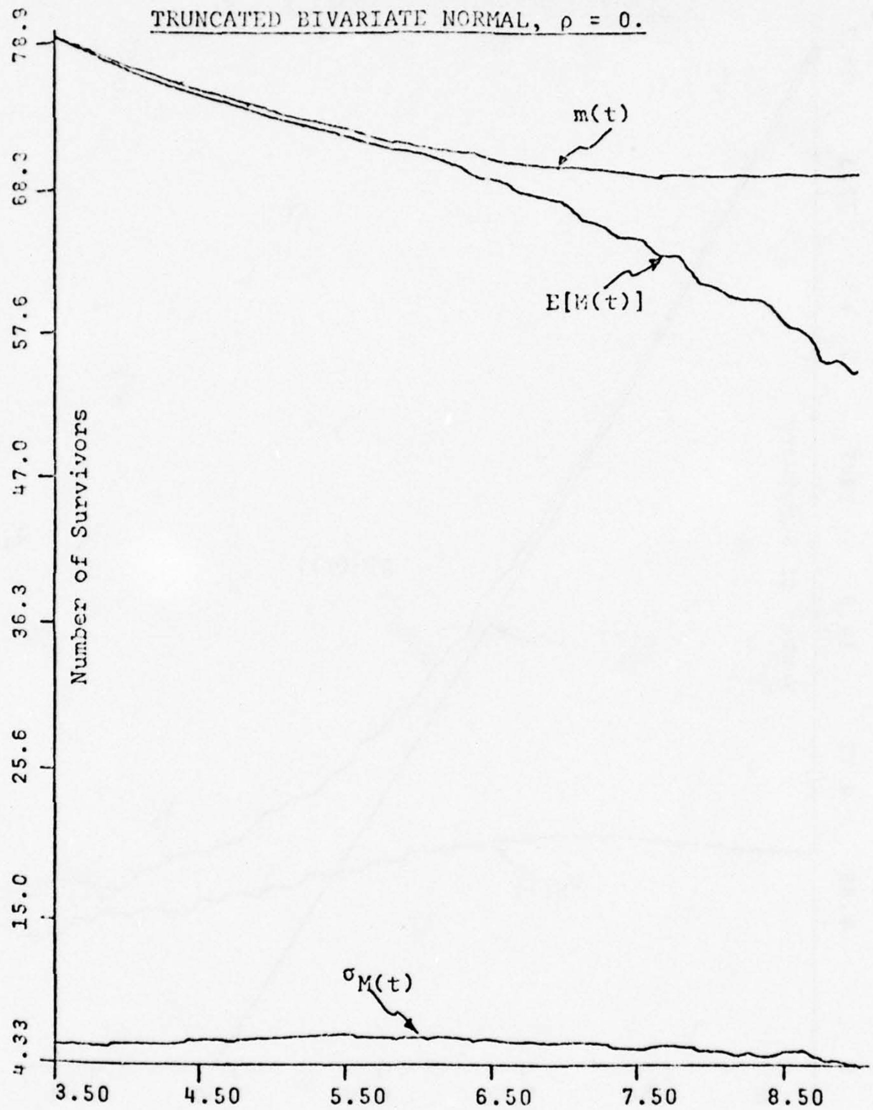
In this section we shall assume all the components are combat-oriented, that is, all are capable of destroying an enemy unit or of being eliminated by an enemy unit, i.e. tanks, trucks, artillery, men, etc.

Thrall, [7], studied the numerous complications which arose in deciding priority orderings of enemy components. For example, Blue tanks may be ordered to fire at Red planes first, then at Red artillery, then at Red tanks, etc. We shall assume that attacks shall be directed at any observed enemy unit, with no hostile component having a priority of being attacked over any other hostile unit. Moreover, no components shall receive reinforcements once the battle begins.

FIGURE 3.1A

RANDOM INITIAL VALUES DISTRIBUTED AS

TRUNCATED BIVARIATE NORMAL, ρ = 0.



TIME × 10^{-1}

BLUES

FIGURE 3.1B

RANDOM INITIAL VALUES DISTRIBUTED AS

TRUNCATED BIVARIATE NORMAL, ρ = 0.

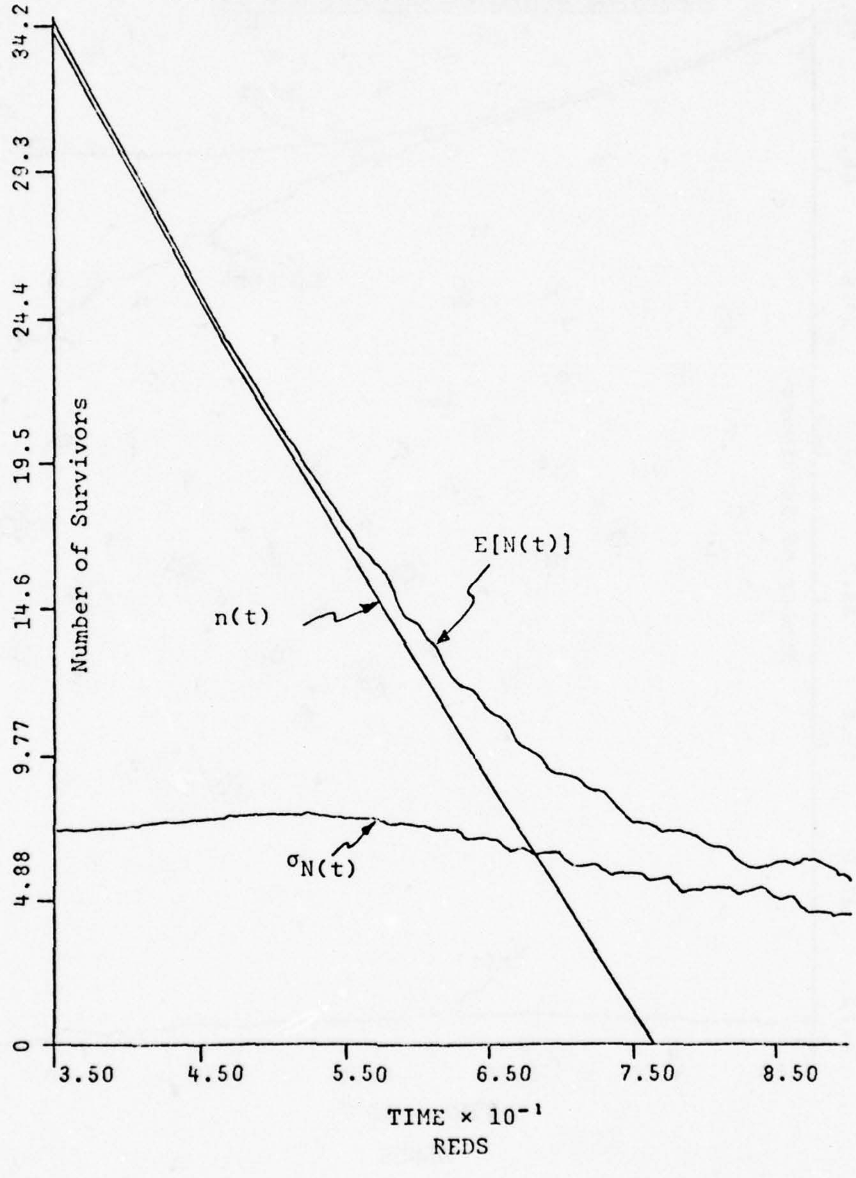
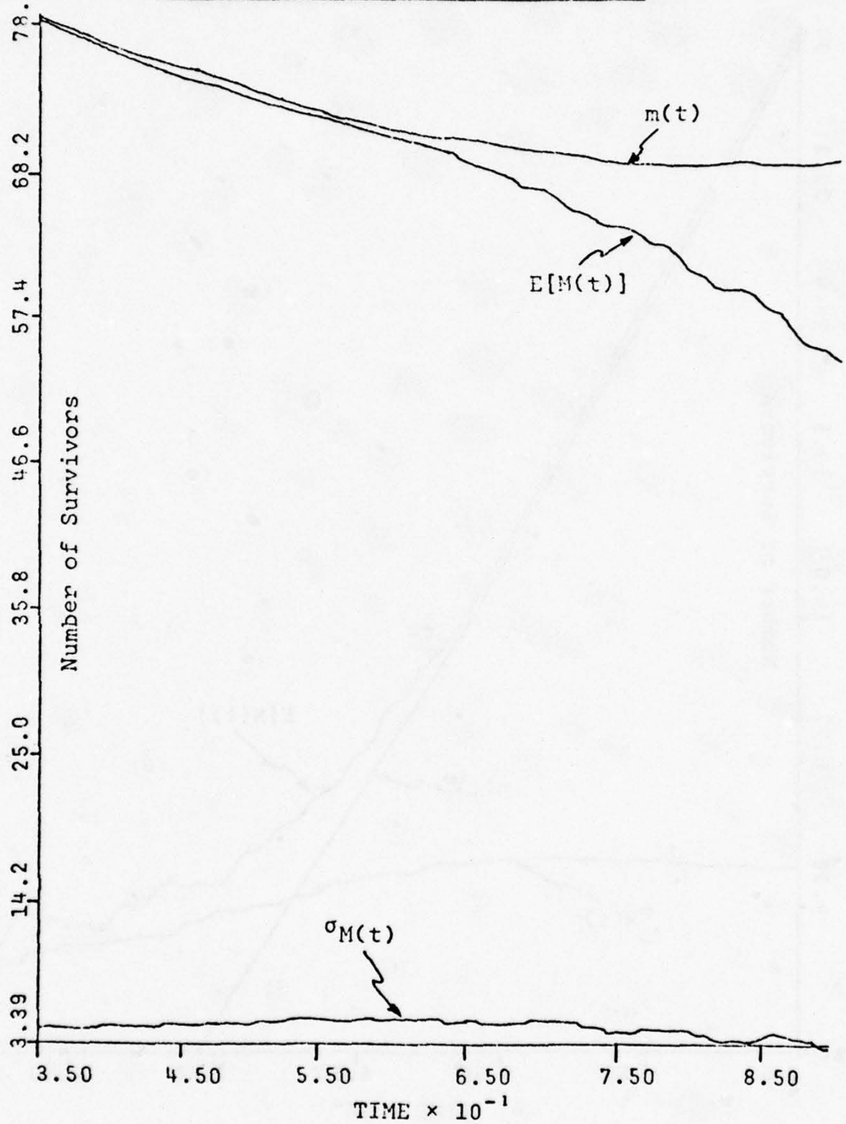


FIGURE 3.2A

RANDOM INITIAL VALUES DISTRIBUTED AS

TRUNCATED BIVARIATE NORMAL, ρ = .5

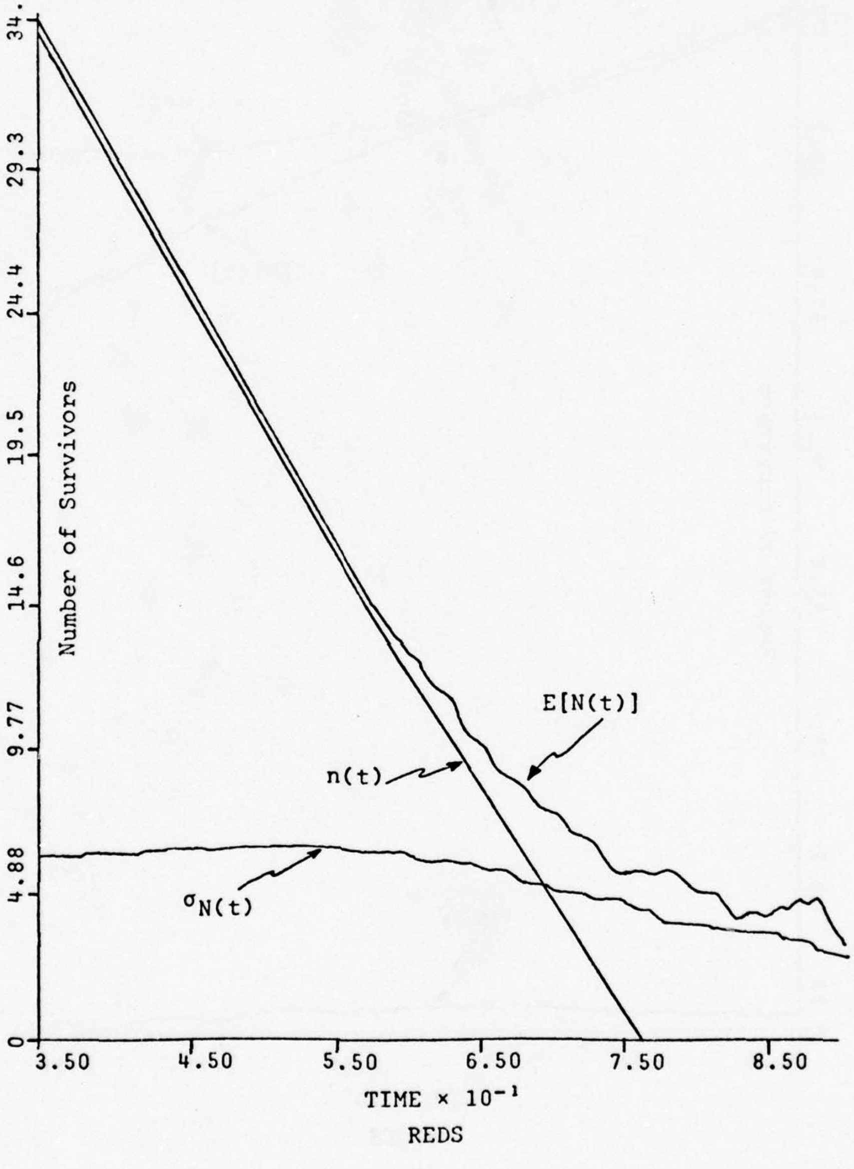


BLUES

FIGURE 3.2B

RANDOM INITIAL VALUES DISTRIBUTED AS

TRUNCATED BIVARIATE NORMAL, ρ = .5



Before stating the Linear Law Lanchester model, a brief discussion of a previous mathematical analysis of heterogeneous forces is in order. From Thrall, [7], the following terms are defined or derived:

S_{ij}: set of those $\ell(1 \leq \ell \leq q)$ such that Red component ℓ has a higher priority than j for Blue component i,

α_{i1}: visibility coefficient for Red ℓ against Blue i,

τ_i: firing period for Blue i,

and

K_{ij}: elimination probability for Blue i against Red j.

From the above, the following information was obtained:

$e^{-\alpha_{i1} n_1 \tau_i}$: probability that a member of Blue i sees no members of Red ℓ in the firing period τ_i, where n_1 is the number of units in Red component ℓ,

$q_{ij} = e^{-\Sigma\alpha_{i1} n_1 \tau_i}$: probability that a member of Blue i sees no members of any Red ℓ, $\ell \in S_{ij}$,

$P_{ij} = 1-e^{-\alpha_{ij} n_j \tau_i}$: probability that a member of Blue i sees at least one member of Red j,

$\nu_{ij} = K_{ij} q_{ij} P_{ij}$: probability that a member of Blue component i destroys a member of Red component j, and

$\frac{m_i \nu_{ij}}{\tau}$: expected attrition to Red component j from Blue component i.

From the above, the total attrition of Red component i is developed by taking the sum of the above $\frac{m_i \nu_{ij}}{\tau_i}$, which are averages. Hence, we obtain

$$\frac{dn_j}{dt} = - \sum_{i=1}^{p} \frac{m_i \nu_{ij}}{\tau_i}$$

or, using matrix notation,

$$\frac{d\underline{\underline{n}}}{dt} = - \underline{m}\Gamma$$

where

$$\Gamma = \frac{\nu_{ij}}{\tau_i} \ .$$

A similar approach is used to find $\frac{d\underline{\underline{m}}}{dt}$.

We shall improve this approach by treating these rates $\frac{\nu_{ij}}{\tau_i}$ as random variables, as was done for the homogeneous case in section 3.1. In Thrall, [7], the linear and quadratic laws were intermingled into the model according to whether $\alpha_{i1}n_1\tau_i$ and $\alpha_{ij}n_j\tau_i$ were large or small. For this part of the paper, we shall assume that $\alpha_{i1}n_1\tau_i = 0$ because $S_{ij} = \phi$, since no priorities are given. The heterogeneous linear model is

$$\dot{U}(t) = \begin{bmatrix} -A_1 & 0 & 0 \dots 0 & -A_{11} & -A_{12} & \dots -A_{1q} \\ 0 & -A_2 & 0 \dots 0 & -A_{21} & -A_{22} & \dots -A_{2q} \\ \cdot & & & & & \\ \cdot & & & & & \\ \cdot & & & & & \\ 0 & 0 & 0 \dots -A_p & -A_{p1} & -A_{p2} & \dots -A_{pq} \\ & & & & & \\ -B_{11} & -B_{12} & 0 \dots -B_{1p} & -B_1 & 0 & \dots \ 0 \\ -B_{21} & -B_{22} & 0 \dots -B_{2p} & 0 & -B_2 & \dots \ 0 \\ \cdot & & & & & \\ \cdot & & & & & \\ \cdot & & & & & \\ -B_{q1} & -B_{q2} & 0 \dots -B_{qp} & 0 & 0 & \dots -B_q \end{bmatrix} \underline{U}(t) \qquad (4.1)$$

where the random variable rates are

(i) A_{ij} (B_{ji}) is the rate at which a Red unit j (Blue unit i) destroys a Blue unit i (Red unit j) per unit time,

(ii) A_i (B_j) is the operational rate loss per unit Blue (Red) per unit time,

(iii) $\underline{U}(0) = (M_{10}, M_{20}, \ldots, M_{p0}, N_{10}, N_{20}, \ldots, N\ \ )^T$ is the vector of random initial conditions;

and

$$\underline{U}(t) = (M_1(t), M_2(t), \ldots, M_p(t), N_1(t), \ldots, N_q(t))^T.$$

Equation (4.1) with the random initial conditions $\underline{U}(0)$ is a system of p + q linear differential equations, which is solvable by the method used in the solution of system (1.9) - (1.10). Assuming an a priori probability distribution for

$$\underline{C} = \underline{U}(0)$$

and

$$\underline{A} = (A_{11}, A_{12}, \ldots, A_{1q}, A_1, A_{21}, \ldots, A_{2q}, A_2, \ldots,$$
$$B_{q1}, B_{q2}, \ldots, B_q)^T,$$

namely,

$$f_0(\underline{c}, \underline{a}),$$

we can find the joint probability density function for $\underline{U}$ and $\underline{A}$ from the equation (2.9) and the probability density function $f(\underline{u};t)$ from

$$\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \quad \int_{-\infty}^{\infty} f(u,a;t)\,da_{11}da_{12}\ldots db_q.$$

Expected values are calculated in an analogous manner to those found in section 2.

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FIGURE 3.1A

RANDOM INITIAL VALUES DISTRIBUTED AS

TRUNCATED BIVARIATE NORMAL, ρ = 0.

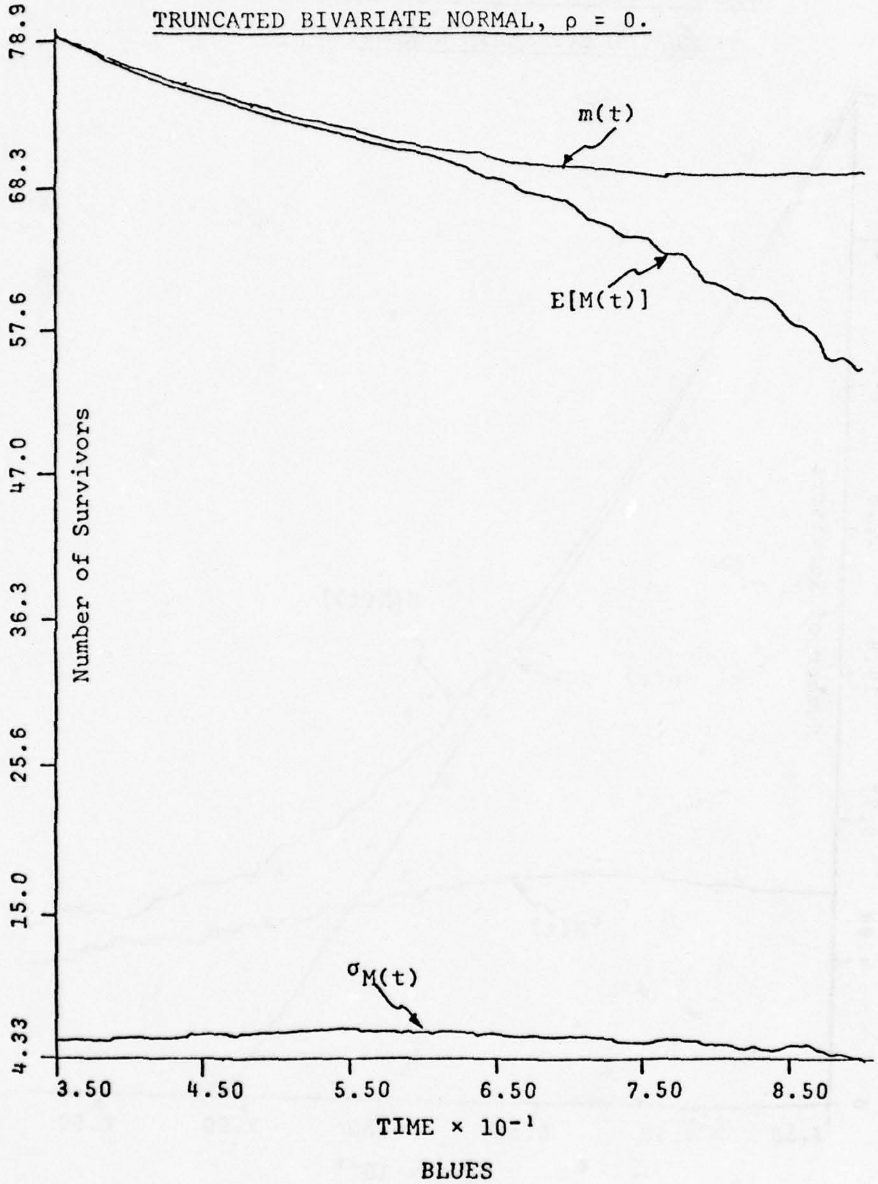


FIGURE 3.1B

RANDOM INITIAL VALUES DISTRIBUTED AS

TRUNCATED BIVARIATE NORMAL, $\rho = 0.$

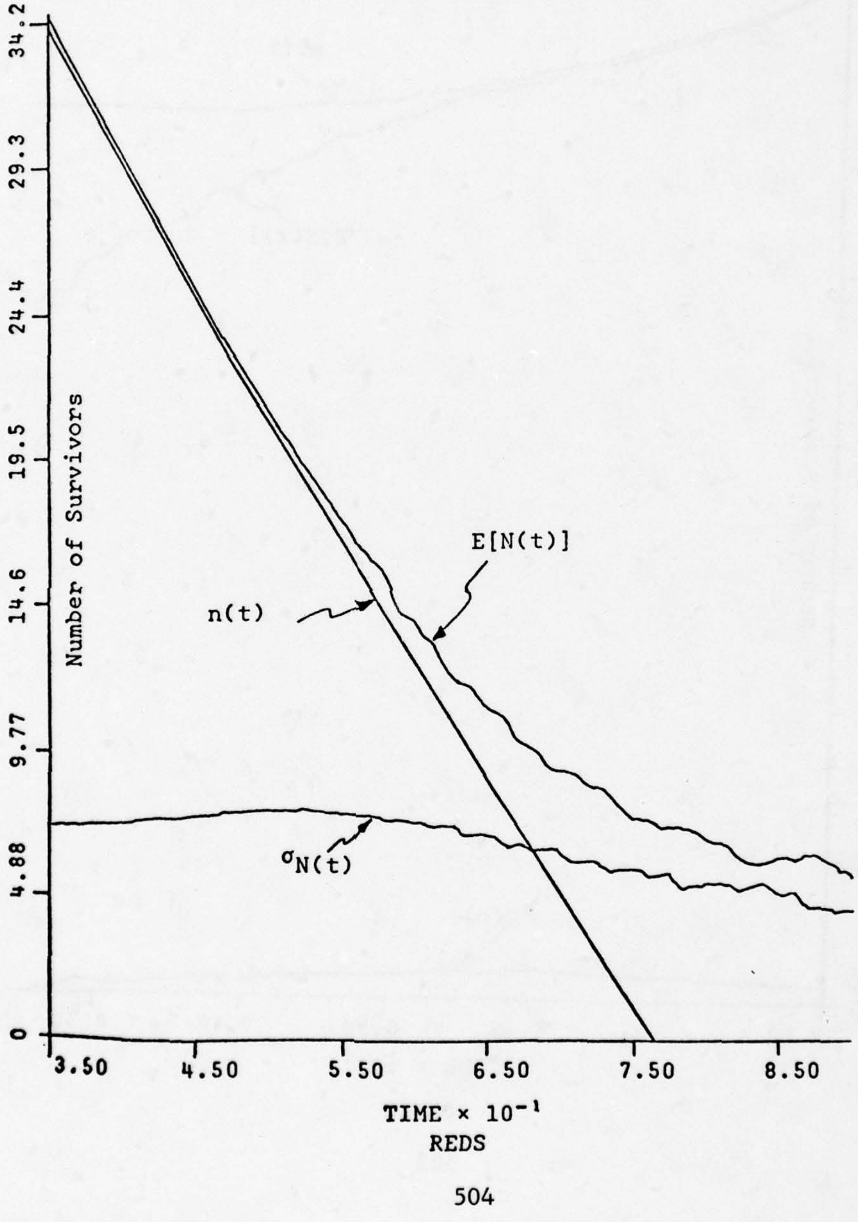


FIGURE 3.2A

RANDOM INITIAL VALUES DISTRIBUTED AS

TRUNCATED BIVARIATE NORMAL, ρ = .5

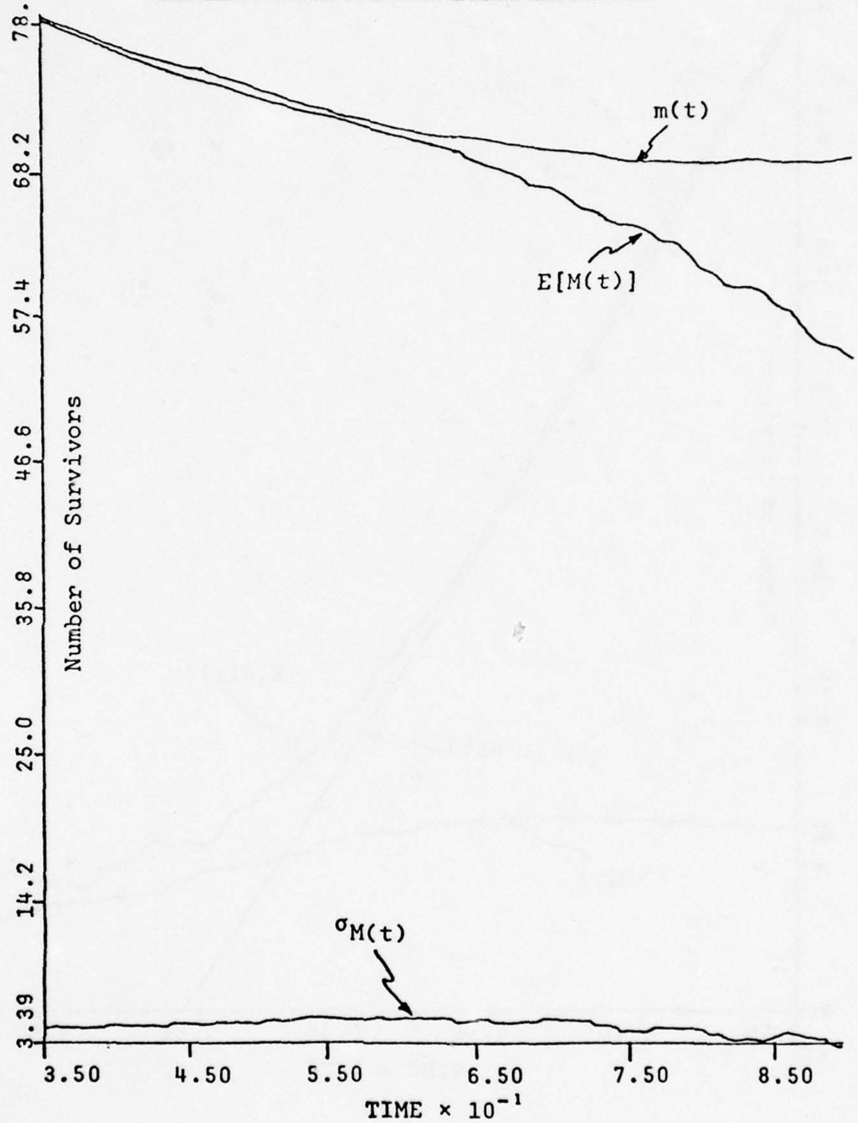
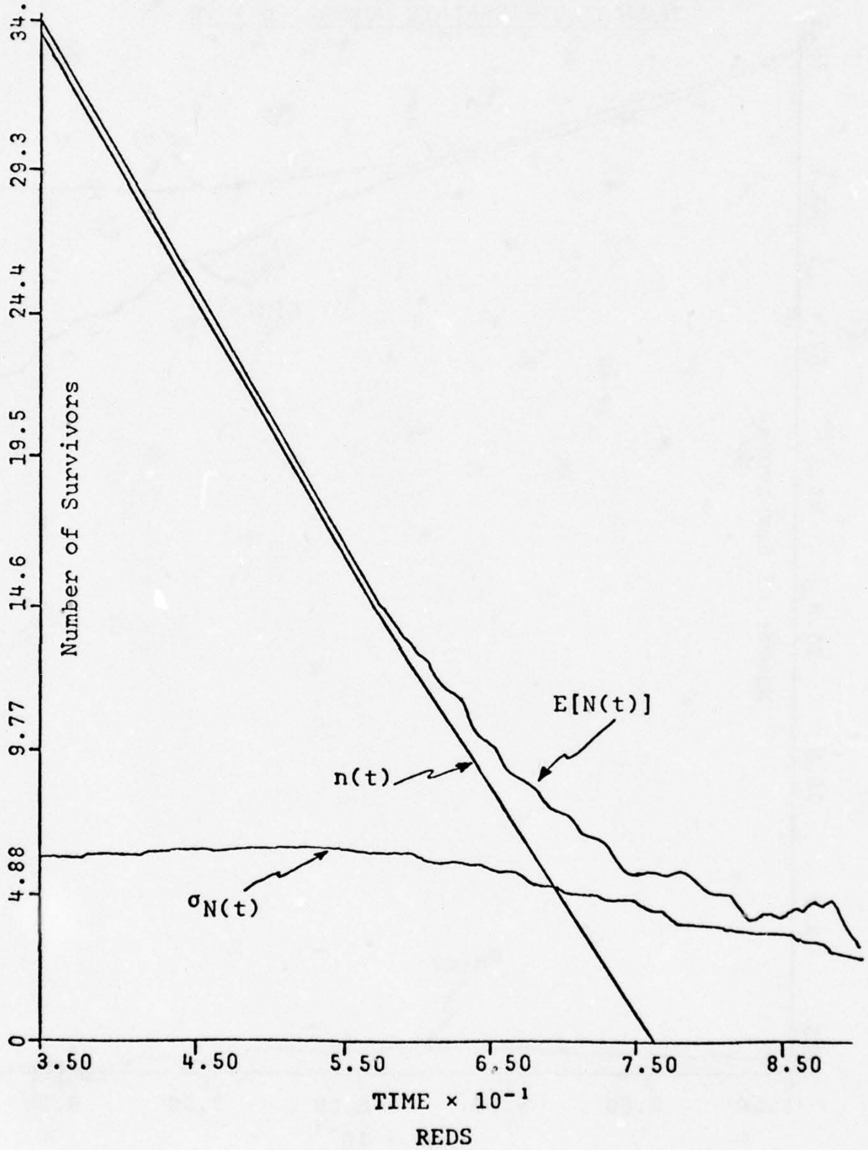


FIGURE 3.2B

RANDOM INITIAL VALUES DISTRIBUTED AS

TRUNCATED BIVARIATE NORMAL, ρ = .5



AN EXAMPLE OF DATA-POOR MODEL "VALIDATION"*

by JAMES R. THOMPSON
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During this conference, I have repeatedly mentioned the futility of a data-free model "validation" process. An example of this can perhaps be given by considering a study which was not data-free but only data-poor. In 1954, J. H. Engel [1] published a well known study which attempted to verify the application of Lanchester's first law to the casualty data of the Japanese and American sides during the battle of Iwo Jima. The model he considered was

$$\frac{dx}{dt} = P(t) + Ay$$
$$\frac{dy}{dt} = Bx \qquad (1)$$

where X and Y denote the American and Japanese strengths, respectively, and P(t) denotes resupply to the American side. Although incremental casualty data was available for the American side, there was no such information for the Japanese side -- only rough estimates of the strengths at the beginning and end of the battle. Inasmuch as the American side suffered less than 30% casualties, it is not surprising that the first law equations gave results which agreed very closely with the observed values of X(t). However, the test of the model should lie also with the reproducibility of the Y(t) values which were reduced over 95% during the course of the battle. (Engel assumes that the Y force was reduced to zero in 36 days. However, constant Japanese resistance -- however ineffective -- lasted for over a month after the end of the 36 day period. On the day after the battle was

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"over", 20 Japanese were killed in a banzai charge. Prisoners were taken daily during the month of April 1945 with as many as 70 taken on one day, pp. 284-287 [2].

Fortunately, we do have a piece of information as to the Japanese strength during an intermediate point of the battle. On the 21st day of combat the Japanese commander, General Kuribayashi, estimated that he had around 1500 men (p. 268 [2]). Using the quadratic law, we obtain a figure in excess of 8550 -- almost six times Kuribayashi's figure.

It is not unreasonable that some scattering of forces would cause Kuribayashi's estimate to be on the low side, but not by a factor of six. In fact the reduction of the Japanese force by approximately 20,000 in the first 21 days followed by a reduction of around 10% of that figure during the next 15 fays hardly indicates that Lanchester's first law with constant coefficients is operative. One is tempted to try Lanchester's second law

$$\begin{aligned} \frac{dx}{dt} &= P(t) + Axy \\ \frac{dy}{dt} &= Bxy. \end{aligned} \tag{2}$$

Since Lanchester's second law never leads to annihilation of either side, we shall not try to obtain constants which give $Y = 0$ for $t = 36$ but instead closely match the first law values of X and Y for $t = 35$. A comparison of the two laws is given in Appendix I. We note that for $t = 21$, the Y force has a value of 2350, considerably closer to Kuribayashi's estimate of 1500 than was the first law figure of 8550.

There is certainly no attempt here to advocate that the second law is the correct model for the battle of Iwo Jima. The X values given by the first law model are generally closer to the actual values than are the second law values -- though X relative errors are small for both models. The point is that an excellent fit of a model to the force values of one side -- and that side the least scathed -- does not mean a great deal.

It is suggested that the mixed law

$$\frac{dx}{dt} = P(t) + Ay$$
$$\frac{dy}{dt} = Bxy \tag{3}$$

might be useful in combats with disparity of force strengths. It is also suggested that the first law might be generalized by considering

$$\frac{dx}{dt} = P(t) + k(t)Ay$$
$$\frac{dy}{dt} = \ell(t)Bx \tag{4}$$

where $k(t) = \%$ of effective possible fire directed by force Y against force X.

$\ell(t) = \%$ of effective possible fire directed by force X against force Y.

This would handle such factors as the fact that in a battle with disparate force ratios -- as at Iwo Jima -- much of the stronger force will be inactive.

In general, a mixed force operation such as Iwo Jima (where naval gunfire was extremely important) should probably be handled via heterogeneous force equations.

REFERENCES

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[2] Newcomb, Richard F., Iwo Jima, Holt Rinehart and Winston, New York, (1965).

APPENDIX I

First Law			Second Law		
A = .0545	B = -.0107		$A = -1.90 \times 10^{-6}$	$B = -1.91 \times 10^{-6}$	
t	X(t)	Y(t)	t	X(t)	Y(t)
1.0	52833	21217	1.0	52937	20432
2.0	51692	20658	2.0	51017	18502
3.0	56582	20078	3.0	55420	16715
4.0	55504	19479	4.0	53599	15066
5.0	54458	18891	5.0	52160	13619
6.0	66446	18244	6.0	63739	12191
7.0	65471	17538	7.0	62364	10808
8.0	64534	16843	8.0	61168	9605
9.0	63634	16157	9.0	60123	8555
10.0	62772	15481	10.0	59206	7634
11.0	61947	14813	11.0	58399	6823
12.0	61158	14155	12.0	57687	6107
13.0	60404	13505	13.0	57057	5473
14.0	59685	12862	14.0	56497	4910
15.0	59002	12227	15.0	56000	4410
16.0	58352	11599	16.0	55556	3965
17.0	57737	10978	17.0	55161	3567
18.0	57156	10364	18.0	54807	3211
19.0	56607	9755	19.0	54490	2893
20.0	56902	9152	20.0	54206	2608
21.0	55610	8554	21.0	53952	2352
22.0	55160	7962	22.0	53723	2122
23.0	54742	7374	23.0	53518	1915
24.0	54356	6790	24.0	53333	1729
25.0	54001	6211	25.0	53166	1562
26.0	53679	5635	26.0	53017	1411
27.0	53387	5062	27.0	52881	1276
28.0	53127	4492	28.0	52760	1153
29.0	52897	3925	29.0	52650	1043
30.0	52699	3360	30.0	52551	943
31.0	52531	2797	31.0	52461	853
32.0	52394	2236	32.0	52380	772
33.0	52287	1675	33.0	52307	698
34.0	52211	1116	34.0	52241	632
35.0	52166	558	35.0	52181	572
36.0	52150	0	36.0	52127	518

$$
\begin{aligned}
x(0) &= 0 \\
y(0) &= 21{,}500 \\
P(t) &= 54{,}000 \text{ if } 0 < t \leq 1 \\
&= 6{,}000 \text{ if } 2 < t \leq 3 \\
&= 13{,}000 \text{ if } 5 < t \leq 6 \\
&= 0 \text{ otherwise}
\end{aligned}
$$

Question: There is a method I think to what you say and that is that in all the technical communities we don't have the legal and medical analog of forensic judgment. There are legal experts. There are medical experts. There are accountants who are CPA. There are all manner of professions that require forensic judgments. *We do not have the analog of that in the technical* community. We do not the analog of that especially in the analysis community. I regard engineering as self-regulating. But in this mega world of operations research, which forms as a habit, the signposts are very foggy. The point I am trying to make is that maybe you have become one of those forensic scientists.

Kalaba: By the way, it is interesting that you should bring up legal aspects. I really wondered about that. I wonder if the commander is anywhere authorized legally to surrender any of his responsibility to what any black box says. This is a very interesting question.

Welch: I would like to return to another matter. The problem of cooperation. I assimilated the notion early on of forming plans. I remember the phenomenal statement that that was a creative act. Let me talk about another aspect of the plan. Let me propose that one of the ways in which one can model the military processes that it is an indirect process in which a plan is created. A great deal of time and attention is then spent by people trying to follow the plan. Time is spent by people on top to see if, in fact, people are following the plan. Perhaps, by looking for new information to see if the plan should continue to be followed or perhaps abandoned. But, in fact, the plan becomes an essential organizing feature. That bears on the question of cooperation. It's not at all clear to me but that it isn't true that the real enemy of effective military operation is chaos, not bad decisions. This goes along with a lot of homey type examples that say, "For Christ's sake get your act together - any act will do." This, in fact, came up in a very specific way. We once wrote down a

game theoretic solution to a theatre level air war which was an n-state game and we were able to handle 20 or 30 strategies on both sides. We generalized that to the full land and air situation. We ostensibly could write down the game theoretic solution to any arbitrary size combat in those terms. The only trouble was that it resulted in an n-state game in which the number of strategies was any arbitrary number of millions you might imagine. There wasn't any way to deal with that size game matrix. All of which was noted as nonsense anyway because in fact many of the matrix entries - by far the majority - were nonsense because they were monstrosities or they were chaotic or they were trivial in the sense that what the infantry company did on the left flank was total unrelated to what was happening on the right flank. The only way to try to get at that, was to recignize that things weren't done that way. Each echelon in the hierarchy of command makes general statements that are modified on their way down. I kept hoping that you would say something about the subject of chaos and cooperation. It seems to me that that is a whole new perspective on the business. We've been thinking about decisions in a optimum decision sort of way. It isn't clear to me but that the first name of the game is to get some coherence and cohesiveness. It doesn't make all that much difference how optimum it is. The optimum chaotic solutions are so atrocious that if you could simply pluck those out then that's 90% of the command and control operation.

Anderson: After Gen Welch's long speech, I would like to return to your theme of education in this area because that is a particularly pertinent subject. At this time DOD has just recognized the need for specific education in the area of command, control and communication. One of the things I am afraid of looking at the evolution of this is that as past discussions of WWMCS noted, the communicators are the only ones ready and willing to rush forward with solutions and perscriptions. Having looked at this problem for some time, I think that the third C in C^3 ought to be

a small c in comparison to the other two. I would be interested in your ideas as to how one should go about formulating a curriculum for this sort of activity and getting the involvement of some of the people who have spoken at this conference and who I think have some ideas that ought to be better assimilated into the C^3 educational structure.

Kalaba: Of course we will try to do this. That's why I assume you are only talking about people who already have an MBA or something of that sort and are already well versed in OR and such. I think one has to get down to the nitty gritty of having people who are concerned with resupply or something and who really want to solve the problem and who are really going to be involved in doing research themselves. They should work right along with people in these areas. They really have to do the research themselves. It's the spending of those months, or several years, really doing an OR job, seeing that through from beginning to end. Supervising is not the same as doing it. Seeing how computers are usually out of order, seeing what kind of solution one ends up with as compared to what one hoped to get in the beginning. I think that that kind of seasoning is going to make one tough cookie to deal with later on. I think we are in real deep trouble unless we have real tough cookies like that who can speak from firsthand experience. You can be in the Air Force all you want, but I spend all my time in the computer laboratory. You can't really imagine what that's like and I can't imagine what your situation is like. I think we've got to have some people who can do these things, where you can't pull the wool over their eyes at all. I think the people who I have seen around here are the ones who ought to discuss these further plans. The Air Force, the academies and private think tanks have to share the responsibility here. They have to be represented in this educational system.

Thrall: We have seen a process of model building. We may

decide to reject the model or we may decide to go on and whether it's worth trying to improve it. If it is, you go on, otherwise you stop. If we carried out that process, we'd never be able to use a model. I think you must have someplace where you're going to use the model, even though you may not be completely theoretically happy with it. A good example is in physics. We've used F = ma for a good bit of our terrestrial dynamics. We've built our automobiles with it, all kinds of things. It worked quite well, even though we know we have to put in the relativistic correction. I think you have to ask another question at that stage. That is, are the imperfections in the model such that we can't even begin to use it? At the same time that we are continuing the research to perfect the model, we also have to have some sort of criterion as to when we are going to use it. I think this is where I have to question Clyde's statement. He said you never get a model that you will accept scientifically. But you wouldn't be in the model business if you wouldn't somehow find a place where you could use it. What is the criterion for usability of the model as opposed to theoretical acceptance of the model?

Hartley: It seems to me that the question of whether the model is good enough is one of statistical efforts that arise in using a model. I think those statistical efforts can be measured and translated into risks that are involved in using an approximate model. However, it seems to me also that even if all this is done, it usually will be found in models in which human elements are involved, that the model itself will require a very large number of variables. It all depends on what levels these variables are. Weapons systems are dependent on the weather - is there fog or is there not fog - the so-called state of the world variables. If you are planning for the future and using such models involving a large number of variables, for many of these variables it is completely unknown at which levels they will be. What are the battle situations that you will encounter

in the future? You can only make guesses. It turning back to Dr. Kalaba's suggestion that there should be a team of scientists involving the law and then evaluating systems with regard to their merits. One system may be very good indeed if you make certain assumptions about what the state of the world variables will be in the future that you will ask to encounter. People in companies who want to make a decision as to whether a new product should be put on the market or not have units called venture analysis. Venture analysis people try to do their best to build a model to predict what profit could be made from such a new product. They have in these models a large number of state of the world variables that they are not able to predict. What do they do? They present their assumptions, their model to management and it is management, the real high up people in the company, who make the decisions as to the likelihood whether certain state of the world variables will be encountered or not and at what level. I mention what that comes down to is the hard core decision maker is still needed to make a judgment as to what is the likelihood of certain situations that are going to be encountered by the system in the future. I don't think a scientist can make a judgment as to what level these unknown state of the world variables, as they are called in model building, will be at. You need somebody who has a very good judgment - a political judgment, an economic judgment, a technological judgment - as to what the system will encounter.

Modrick: I'd like to make one comment about the relationship between models and then two or three others that are a little more general but still fairly closely related to the sort of thing we were trying to get at. As far as models are concerned, I don't think we ever reject a model, I think we substitute one model for another. I think the evaluation of models is largely relative. It's true that we can apply an absolute statistical criterion but when it boils down to the practical usefulness of a

model, I think the statistical criteria are not really the most useful ones. They are judgmental and in that sense, if model B is better than model A or predicts what we are interested in more successfully then we will reject model A and begin using model B. Certainly in the area of psychology, there is a long history of relatively bad models for predicting how successful someone might be in a particular job. They continue to be used until we find a model that will predict more successfully. That's point one. Point two is that we've been discussing the general domain of models for command and control. I think there is a distinction that might be made that has occasionally cropped up. That is a model for the decision maker as opposed to a model for the data generating process or for the environment. Dr. Kelly described what I think of as primarily a model for the decision maker. His value structure, and trying to represent in an online decision the utility structure that he might use himself. An aside with respect to that: the way in which Dr. Kelly presented that it was rejected fairly substantially on the grounds that we don't want to substitute an arbitrary model for the decision maker's decisions. But, in fact, the way such a model would be developed, would be to have the commander himself - and this would be unique to each commander - sit down with the utility structure, do the sensitivity analysis himself and decide either that he liked that utility structure and the Bayesian model underlying the structure represented his own point of view. Until he was completely satisfied that that was representative, he would be very reluctant to use it. The point is, in the of model they were trying to build, it is possible to do that in advance, so that when the actual online use occurs he is in a position not to accept it as if it were gospel but to understand what's behind it and accept it as a representation of the information he himself introduced into the model. In the model Dr. Kelly presented, there is a representation of the state of the world in the form of a set of probabilities and it's from that

one fact that I am referring to a model of the environment. That is, in defining the state of the world, the environment must be represented. I believe that many of the models that have been discussed here have been models for the underlying data generating process or state of the world. I think that is a quite useful exercise and one that is needed. My perspective with respect to that is a little different than the attitude that would be typical of an OR specialist. Optimization algorithms are fine for presenting the recommended solution but what the commander needs is a better understanding of the underlying space in which that optimization took place. That is, he heeds to be able himself to explore sensitivity analyses and sya, how sharp is the peak at that optimum? What's the effect on all the numerous variables on the shape of that space? Suppose I change various components. The way in which a model of the environment could be quite effectively used is as an educational process to build in the heads of the decision maker a clear picture of the way the environment changes, or the impact of various kinds of environmental changes on some kind of optimization process. I believe this is a position that is reflected in some of the material Dr. Tolcott talked about and some of the work ONR is sponsoring, where, rather than getting optimal solutions, the display that will be provided to the decision maker would be a display of the space in which that optimization takes place. And give him a broader perspective from which to make his own judgment rather than making the judgment for him.

V. SUMMARY

A PROPOSED EDUCATIONAL PROGRAM FOR COMMAND
CONTROL AND COMMUNICATIONS

by DR. MICHAEL G. SOVEREIGN
Naval Postgraduate School, Monterey, California

The primary purpose of this workshop has been to sharpen the research focus on decisions in C^3. However, I believe that there is a more fundamental problem which has been identified during the meeting. That problem is that the operators of the C^3 system and the designers of the system are not on the same wave length. This open switch makes it difficult for researchers in the information and decision sciences to even get into the loop. I would maintain that this problem is one of education or lack thereof. Professor Bob Kalaba of USC has apparently reached a similar conclusion. Lieutenant General Creech of the Electronics Systems Command identified the problem on Thursday when he said "that we need to tighten up the dialogue between operators and designers, have more interaction but stay out of the other sides work." We must educate the C^3 community to distinguish the proper roles of the elements of the community and to perform their own roles competently. Rear Admiral Engen also said, "Don't let the system gorw like Topsy just because we have the technology." Rear Admiral Kinnear added that we must get articulation of what the operators want in order to affect decisions. These statements all point to the need for a more thorough preparation for the officers who are the users of the national C^3 system to enable them to talk to the engineers without telling the engineers how to do the design. One reason that an educational program is necessary is that the C^3 community is not now cohesive or well-defined. We have heard several speakers mention the sociological problem. It is difficult to become a C^3 professional if you can't define it.

I would like to establish the seriousness of this situation with a few more quotations from Thursday's presentations. Major General Jasper Welch, Assistant Chief of Staff for Studies and Analysis said "at the budget decision level C^3 is out of control." Rear Admiral Engen said that the Navy has two problems in C^3:

1) Operators don't participate in architectural planning of the system.
2) Systems designers just plunge into the hardware without determining the needs.

Professor Kalaba said today, I believe, that we need "encoder's and decoder's" to help the dialogue. The educational preparation of officers from all of the services for positions in the planning of C^3 systems has recently been under active consideration by the Director, Telecommunications and Command and Control Systems, OSD. Although no definite decisions have been made, a graduate-level program for officers at 0-4 and above is under consideration. The Naval Postgraduate School, among others has been asked to explore the development of a suitable curriculum. I would like to present certain aspects of that curriculum today and get your reactions to it.

The general process for developing a curriculum is shown in Figure 1. The billet requirements are currently being developed by OSD and the joint commands. A first iteration of the skills list has been established and is shown as Figure 2 along with a statement of a general objective. The Naval Postgraduate School is currently developing a C^3 curriculum conception response to this requirement. This curriculum will, by necessity, be influenced by the related existing curricula at the Naval Postgraduate School. These include those of Figure 3. For example, an existing curriculum in communications with approximately 40 students currently on board is shown as Figure 4. However, an important departure in the new proposed curriculum in C^3 is the emphasis on operational capability and the ability to think of improvements in C^3 as related to their contribution to military effectiveness. The

FIGURE 1

JOINT COMMAND, CONTROL & COMMUNICATIONS
CURRICULUM DEVELOPMENT

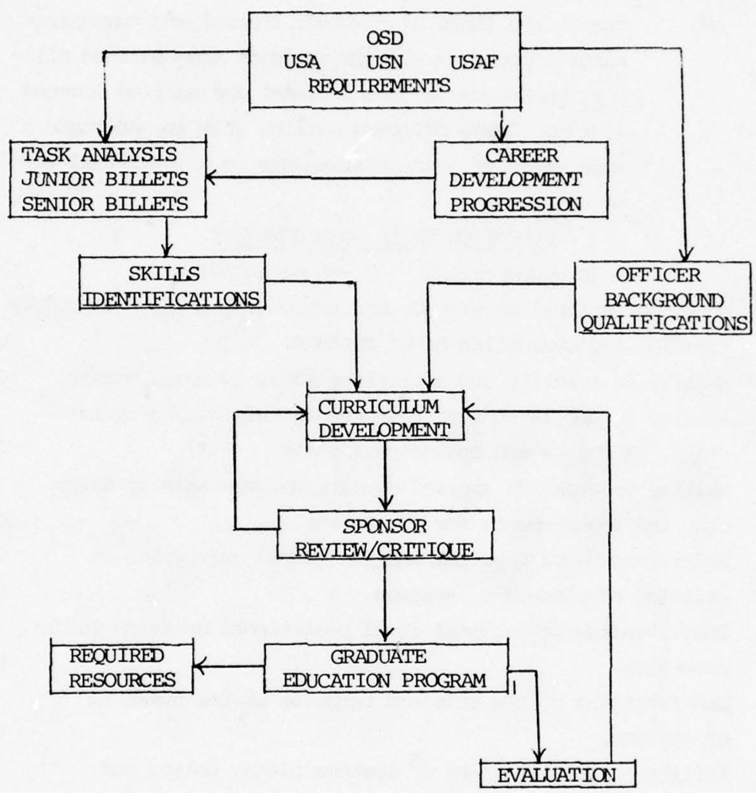

FIGURE 2

COMMAND, CONTROL AND COMMUNICATIONS SYSTEMS CURRICULUM

OBJECTIVE: To provide officers, through graduate education, with a comprehensive operational and technical understanding in the field of command, control and communications systems as applied to joint and combined military operations at the national and unified command levels. These officers will be able to undertake a wide range of joint assignments in C^3 over full span of a career.

EDUCATION SKILL REQUIREMENTS

(C - Competency -- U - Understanding)

. Apply operational experience and analytical methods in specification and evaluation of C^3 systems.	C
. Ability to identify and articulate joint C^3 requirements.	C
. Ability to use lessons of past events in planning operations, exercises and operational tests.	U
. Ability to evaluate applied operational research to determine the requirements for C^3 systems.	C
. Understanding of physical and analytical principles of existing or planned C^3 systems.	U
. Understanding of national level operational decision-making processes.	U
. Understanding of the role and behavior of the human in C^3 systems.	U
. Ability to develop joint C^3 systems plans, policy and requirements.	C
. Ability to manage C^3 operations, including an understanding of ADP software management.	C
. Possess understanding of DOD and the joint command structure and National Security Affairs.	U
. Possess understanding of Defense acquisition processes.	U
. Ability to adapt C^3 system design and operations to electronic and physical vulnerabilities.	C

- Possess understanding of C^3 and intelligence, logistics, management information systems relationships and inter-operations.

FIGURE 3

NAVAL POSTGRADUATE SCHOOL CURRICULA

RELEVANT TO C^3	
XX	OPS RESEARCH/SYSTEMS ANALYSIS
XX	COMPUTER SYSTEMS
XX	COMPUTER SCIENCE
X	METEOROLOGY
	OCEANOGRAPHY
X	ANTI-SUBMARINE WARFARE
	WEAPONS SYSTEMS TECHNOLOGY
	WEAPONS SYSTEMS SCIENCE
	UNDERWATER ACOUSTICS
	NAVAL ENGINEERING
X	ENGINEERING ELECTRONICS
XX	COMMUNICATIONS ENGINEERING
	AERONAUTICAL ENGINEERING
XX	TELECOMMUNICATIONS SYSTEMS
X	NATIONAL SECURITY AFFAIRS
	SYSTEMS ACQUISITION MANAGEMENT
X	NAVAL INTELLIGENCE
X	ADMINISTRATIVE SCIENCE/MANAGEMENT
X	ELECTRONIC WARFARE

FIGURE 4

COMMUNICATIONS ENGINEERING/TELECOMMUNICATIONS SYSTEMS

	Curricula Components
Electrical Engineering	Electrical Engineering Fundamentals Pulse & Digital Circuits Microwave Devices Electromagnetic Engineering Advanced Network Theory Advanced Systems Engineering
Communications	Communications Technology Electromagnetic Compatibility Advanced Digital Methods in Communications Systems Communications Satellite Systems Engineering Communications Systems Analysis Radio Propagation
Information Processing/ Systems	Introduction to COmputers & COBOL Programming Real Time Information Systems Real Time Information Systems Mgmt.
Organization & Management	Defense Telecommunications Organization and Planning Integrated Defense Telecommunications Systems Introduction to Systems Acquisition Mgmt. Defense Resource Allocation

importance of this capability has been emphasized at this workshop. Dr. Bonder has described the current state-of-the-art of combat modeling. In my opinion the state-of-the-art will not support detailed analysis of C^3 systems; however, there is promise for the future and the proposed program will have a heavy emphasis in what I would term operations analysis in the classical sense, the central pillar in Figure 5. The C^3 officer must be a specialist above all in military operations. Requirements for intelligence information or communications must ultimately flow from the military operation(s) they are supporting or could support. Information, as General Welch pointed out, is useless unless it can affect what the commander would do. Secondly, if the C^3 planner knows what the operational requirements are, he must next be able to model the performance of the C^3 system to see if it can support the requirement. Rigorous model-building skills are required if we wish to avoid the long debates such as that between Dr. Saaty and Professor Coombs. This requires skills in analysis and an understanding of the technology of communications and computers, including the electronic warfare vulnerabilities that were emphasized in this meeting by General Creech. Finally, the C^3 planner must be able to communicate his analysis of the requirement in quantitative performance in functional terms that are meaningful to the design engineer. The IBM study of future WWMCCS architecture discussed here is a prime example of effort in which this type of officer will be called upon to participate.

A C^3 specialist of the type we are trying to develop has a legitimate function in increasing the DOD capability of "crisis management," a term heard often at this meeting. With his emphasis on thinking of what information is useful to the military commander, he should be able to plan better for surge capability, failures, vulnerabilities, information overloads, etc., that will occur in a crisis. However, that is still a planning function not "crisis management" per se. At best we can hope that a trained C^3 officer at the higher levels will realize that <u>no</u> system can

FIGURE 5

INFORMATION/DECISION SYSTEMS

DEFENSE MANAGEMENT

ELECTRONIC WARFARE

COMMUNICATIONS ENGINEERING

OPERATIONS ANALYSIS

INFORMATION PROCESSING

INTELLIGENCE

NATIONAL SECURITY AFFAIRS

provide centralized management and control of all the details for decision makers at every level once the situation deteriorates from crisis to combat. If the trained officer can resist inserting himself into such a position or convince his boss of the necessity to delegate downward, he will have made a great contribution to our capability to manage within our system.

The proposed curriculum would cover the general topics shown in Figure 6. The particular courses which would become the vehicles for these topics have not yet been worked out. I encourage everyone with a stake in the C^3 area to consider the educational problem and give us the benefits of their thoughts on the proposal.

FIGURE 6

POTENTIAL C^3 CURRICULUM COMPONENTS

Operations Analysis

- Operations Planning
  - Analytical tools, modeling, gaming
  - easures of effectiveness, risk analysis
  - DOD/Joint Planning Systems (e.g., JOPS)
- Operations Control/Execution
  - Measures of force availability & readiness
  - Decision analysis - risk measurement
  - Critical intelligence/communications parameters
  - WWMCCS hardware, software, capabilities & limitations
- Operations Evaluation
  - Damage assessment
    - Measurement & statistics
  - Real-time information requirements
  - Case studies of past operations

Communications Engineering

- Circuits, signals, and propagation
- Communications technology including satellite systems
- Signal security & exploitation
- Operational factors: compatibility, systems interference, switching concepts

Computer/Information Processing

- Software, including compilers & operating systems
- Interactive query systems & information structures
- Integration of computer information systems
- Computer graphics and signal processing
- Man-machine interface for computer-assisted problem solving
- Real-time information systems

Management

- Defense telecommunications organization and planning
- Integrated defense telecommunications systems

Intelligence

Threat analysis

American national security policy

Electronic Warfare

Communications systems and countermeasures

Signal intelligence

BRIEF REMARKS ON THE WORKSHOP

by TERRY J. WAGNER
University of Texas

Before making some general comments on the workshop let me begin by stating that my background is that of an electrical engineering professor primarily interested in the applications of probability theory and statistics. My current interests are non-parametric discrimination and estimation and, while these interests certainly are relevant to many specific military problems, they play no major role in tactical command and control problems. I should, then, in no way be considered a technical expert in the area to which this workshop is directed.

Aside from forming the obvious picture of a commander in the field being overloaded with information in combat situations, I got little in the way of specific information from the presentations about tactical command and control problems. This is not meant to be a criticism since, for example, most of the high-ranking officers probably viewed their presentations as mainly sensitizing the technical community to a situation that is a current major military concern. However, if people like myself are expected to be working on mathematical problems which are relevant to this area, there has to be a mechanism where we can really get into these problems to the point of being able to extract useful models. The workshop did not do this.

As for the presentations, I found many of the technical talks of the first two days fairly tangential. For example, it's hard to imagine how the classification and categorization of all types of systems, living or otherwise, is ever going to have any impact on what an admiral does with his fleet in an engagement at sea. Beyond this, there were several talks that left me disturbed to various degrees. They all shared a common characteristic: a

complex situation was oversimplified with an inappropriate model. For example, the thought that someone would actually build a system showing a "bug" on a triangle moving around toward decision apexes astounds me. For one thing, the Bayesian decision theoretic model discussed to arrive at the bug's movement seems totally inappropriate and, for another, this "bug" system has gone beyond what is wanted, a useful presentation of avialable information, not a decision for a ship captain. My guess is that, in a real situation, Admiral Kinnear would just as soon throw the thing overboard as let this bug make his decision.

REMARKS ON THE WORKSHOP

by JESSE ORLANSKY

The meeting at Airlie House was outstanding in bringing together the largest possible community concerned with tactical command and control. I commend you on it, especially with regard to senior military personnel one of whom, probably the brightest, stayed through the entire meeting. Command and control is an unusual area of technology and is among the last to develop a clear technology base. The magnitude of the RDT&E efforts assigned to command and control is not well known. It is an area in which the senior military officer is not only the prime customer, as in all fields, but the final judge of effectiveness and a very significant contributor to the technology of command itself. Command is the main assignment towards which all military training is directed. Of course the military ara also the final judges in most other areas of technology too. But in most other fields, for example, non-military personnel can demonstrate that a particular airplane flies faster or carries more cargo and that's not further debatable. In command and control, however, there is now no other last word, besides military testimony, as to the effectiveness and acceptability of a command system. In this respect, I'm overlooking, of course, some particular technologies inherent in C^3 systems, such as ADP and communications, which are directly measurable. In my view, however, these are necessary but not sufficient means for effective command and control, which must include the commander and his role in management, system structure, information input and decision making. So much, then, for the importance of military involvement in the development of C^3 systems and for their participation in the meeting.

It seems to me that the value of the meeting will be lost unless there is a rapid follow-up on several ideas which became obvious there. They are not necessarily unique to me.

There is a need for a taxonomy of command and control so that any one who works on the field can better understand how his efforts might relate to those of others. Your meeting correctly brought together various talents in ADP, decision making, modelling, communications, costing and requirements with an occasional philosopher, psychiatrist, historian, mathematician and general systems theoretician. This might encourage all to understand where they might contribute and a few to leave the field. At the moment, this taxonomy need only be a pragmatic one subject to change as we learn more about command and control. Preferably, it should be a simple one. Its structure should accommodate problems faced by all services and the JCS at the tactical, strategic, crisis and routine (day-to-day) levels. The taxonomy should be evaluated, as well as illustrated, by examining how it would handle a selected sample of crises and wars. It may be that a usable taxonomy already exists in the work reported at the meeting by IBM on the WWMCCS architecture and perhaps by others in previous studies. If so, I would suggest that such taxonomies be compared and a prototype proposed for use by the RDT&E community.

Major attention must also be given to measures of effectiveness of command and control systems. In fact, the taxonomy suggested above should provide the structure for identifying relevant measures of effectiveness at various levels in C^3 systems. It may turn out that we need many different types of measures of effectiveness. In this case, a catalog is useful for demonstrating that any sub-set of measures concerns only some of the relevant criteria.

Given some performance measures, it would be of considerable interest to compare what they may tell us in reviews of the same events as seen in simulations, exercises, and the real world. I believe that there is much to be learned by insisting on more

quantitative analyses in a field which has largely avoided them so far. It is also important, of course, to plan exercises of command-control systems in such a way as to tell us about system readiness (their usual purpose) and to contribute to a data base to support the design and development of improved systems. I want to emphasize that it is important for R&D personnel to get involved in the planning and analysis of operational exercises of command and control systems. That particular gold mine has been disregarded in a way that would be unacceptable in almost all other fields where we want to know how things really work, such as flight testing of aircraft and missiles, and field trials of radars, guns and lasers. There is also need for manned simulations (for which there are already many installations used primarily for training) as well as modelling, where performance measures can be employed.

Reports on decision-aiding research at the meeting led one to see a clear need for flexibility in design which would permit successive commanders to alter their local command and control systems to suit their own preferences (presumably within limits set by higher, lower and collateral commands with which they interact). I'm not sure that personal preference should be the last word in the design of a military command and control system but there was an expressed need for such flexibility. I suspect that we'll have to honor such requests (or "requirements") until objective performance measures can demonstrate that some ways of doing business are clearly more effective than others.

The other issue clearly brought out by the decision-aiding research is that guidance put out by the black box should be advisory rather than prescriptive. It is a curious fact that all researchers say that their systems offer only advice although the outcomes appear clearly as recommendations to the users. In addition to requiring all commanders to read the fine print on their consoles, I believe the only practical solution is to provide a few big red knobs so that each commander knows that he must enter

his own utility functions, without which the scope would not light up. Maybe, as in some pocket calculators, the lights should go out if new instructions are not provided from time to time.

Finally, I suggest that you could serve the Air Force very well by providing a quick summary of the types of RDT&E suggested by the meeting. Although a summary of the meeting can come out later, plans for RDT&E can be made immediately and, in any case, take a long time before they can take effect. My own suggestions for some RDT&E are the subjects of the various paragraphs above. In addition, I suggest a series of workshops, also taking place soon, to develop the various ideas you collect about what might be done to improve command and control. My point is, of course, that you should almost immediately continue the efforts that got such a fine start at Airlie.

SOME OBSERVATIONS BASED ON THE CONDUCT OF THE WORKSHOP

by JOHN T. DOCKERY
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1.0 Introduction. It was my original intent to address only the general question of effectiveness measures in the context of these proceedings. As the workshop has developed, the applicability of these prepared remarks has receded somewhat because the general question of measures of effectiveness (MOE) has not been illuminated. Therefore, I shall address three elements which I perceive as relating to the definition of problem areas emerging from this workshop. The first will be an outline of an approach which may help organize the subject of effectiveness measures through elucidation of proper definitions. The second will be in the nature of a case history. The third is a look at command and control from an historical perspective.

I will not comment further on the conduct of the foregoing sessions except to second the general remakrs of both Dr. Bonder and Dr. Bracken. In opting to present three elements in short order, I believe I am in the spirint of a workshop. They correspond to a canonical presentation on a technical subject MOE, prepared in advance in my role as an operations research analyst; to a story telling role in presenting a fable in my role as a panel guru; and in the presentation of some half-baked ideas on an historical perspective in my role as a workshop member with a cloistered forum.

2.0 Effectiveness Measures. Armed Services analysis of complex

* These remarks have been edited from the actual presentation. The views expressed are those of the author, and may not reflect the views of the US Army. In the spirit of a workshop the remarks may be couched in a manner intended to provoke discussion.

systems, to include both the subject of weapon mix and the subject of command and control (C/C) of such mixes, is faced with a dilemma of major proportions. Although conventional wisdom retreats in the face of the conundrum that one cannot compare apples and oranges, it is precisely this comparison which any theory of C/C must address. How then is one to formulate MOE consonant with these forced comparisons?

One is compelled to address the question of mix comparison by looking for direction outside the system in question. In general one can treat the mix problem in terms of goal-seeking systems. The comparison then becomes externalized in terms of the efficacy of the various combinations in achieving the stated external goals. This, it seems to me, is the proper framework for C/C analysis. Failure to look externally leads to MOE related only to internal system efficiency. This in turn usually relates only to questions of equipment efficiency.

In cases of conflict there is no means of resolution internal to the system. From the tenor of discussions, which we have heard, it appears that aspects of the control function are not being effectively carried out. Some MOE related to the control function would be useful in quantifying it. Perhaps then the nature of our unease could be measured. It is conventional to construct an "ad hoc" list of candidate MOE. This procedure has been effective as long as one MOE was adequate. Trouble develops when MOE are in conflict.

In order to conduct analyses internal to my agency, I have searched for a proper exposition of MOE which would incorporate goal seeking features. In my search of the literature I found <u>no</u> acceptable mathematical definition of the MOE. The sole exception was an unpublished work of a Mr. Bitter, formerly of the US Army Combat Development Command (now defunct). In his work, Bitter explored the possibility that MOE may obey group properties. In 1973 Pugh and Mayberry discussed a theory of MOE but did not

directly address the question of a definition.*

Lacking any mathematical definition, it is now clear why MOE may be made to perform almost any kind of magic desired. They can exist outside the normal rules of analysis. More amazing to me has been the dawning realization that the total absence of any definition has been of no great concern to the community. Investigating this observation I am led to conclusion that the absence has been acceptable because analysis has rarely involved more than a single MOE. Since a chosen MOE was not combined in any way with other MOE, the question of its mathematical parentage could be ignored, although not always with predictable results. As long as the subject under investigation was familiar, an empirically deduced MOE sufficed. As subjects were undertaken which were more complex and less well understood, the selection of MOE on some intuitive basis faltered. The now widespread practice of <u>a priori</u> selection of an MOE has destroyed the link with empiricism completely. Rather than reveal inherent structure, such selection imposes external structure.

As an indication of problems which can arise in naive combinations of MOE I refer you to the talk of Dr. Coombs, wherein he emphasized the fact that risk is not additive. Analagous problems occur in combination of MOE where they are most often treated simply as real numbers. I do not believe this to be true except in very special circumstances. In particular I have focused on two aspects of MOE.

(1) They always imply some rank order.

(2) They usually reflect hidden structure of the problem.

I am developing a definition of the MOE which defines them in terms of a modelling process.

- Define a set M with at least a partial order on its elements.
- Define a set of goals G which can be related to elements

* OPS Res <u>21</u>, 867 (1973).

of set M by some mapping $p:G \to M$.

The elements of set M are said to be effectiveness measures if they can induce a rank-ordering on the original goal set G via some mapping $f:M \to G$. (There may exist additional sets M_1 and mappings f_1 which induce conflicting goals.)

Sets M & G together with the transformations p & f are then a model of the decision process. The "models" should then form a category as suggested by Mesarovic in his text on General Systems Theory.*

Graphically, we have the following in Figure 1. The analysis problem

* Mesarovic, M. D. & Takahara, Y., General Systems Theory: Mathematical Foundations, Academic Press, 1975, Chap XII.

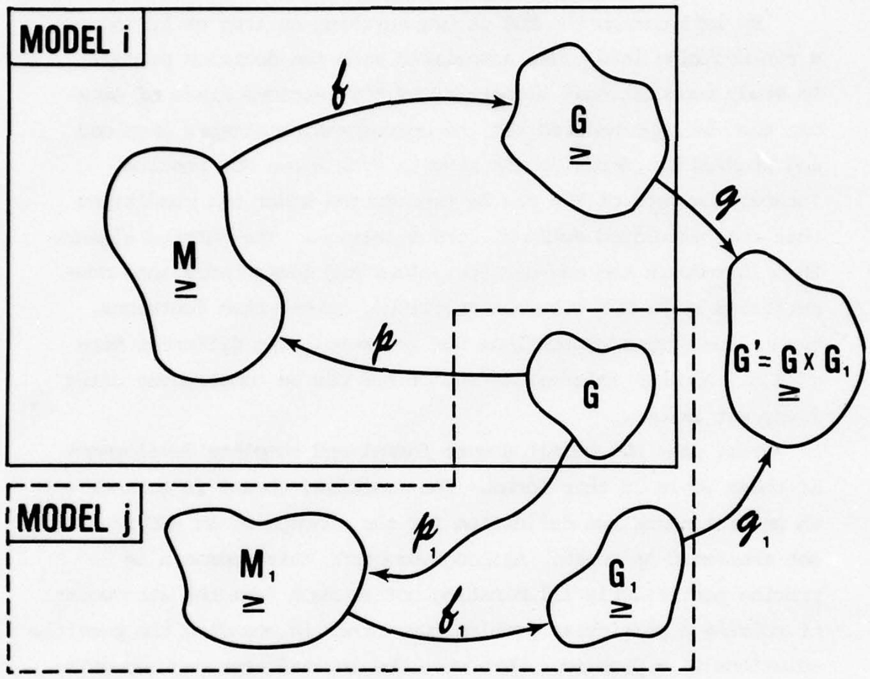

Figure 1. Illustration of the Measure of Effectiveness (Sets M & M_1) defined as part of a modelling process.

with multiple MOE is the reconciliation of the various orderings (G, G_1, ...) of the original goal set G. It is my initial intention to examine the properties of maps $g:G \rightarrow G'$ and $g_1:G_1 \rightarrow G'$ where G' is assumed to be $G \times G_1$.

By implication the MOE is now anything as long as it induces a rankordering into goals associated with the decision process. To study computational properties of MOE, various kinds of sets can then be hypothesized and the corresponding algebra examined and studied by comparing the results with known MOE results. Interesting sets of MOE can be constructed under the conditions that the postulated sets, M, form a lattice. The lattice algebra then introduces the max-min operations and idempotency into computations among MOE values. Relations, rather than functions, become the proper expressions for inter-relating different sets of MOE. Another interesting set of MOE can be constructed using fuzzy set axioms.

Time does not permit a more formal and complete development of these ideas in this forum. The essential thrust is to seek an understanding and definition for the concept of an MOE in a set theoretic approach. Although abstract, this approach is proving particularly illuminating not so much from the standpoint of solving a particular problem but rather in bounding the possible solutions to a problem. Moreover, the investigator can recognize the same problem in a different context. Examining analytical approaches to C/C we find that OR praxis focuses on solving each problem as if it were sui generis. A set-theoretic approach seems to offer some means of reducing complexity by recognition of a smaller number of related problems.

A promising avenue of investigation looks at uncovering the inherent structure of the problem to which the MOE are presumably some kind of indicator. In particular there appears to be some kind of implicit hierarchy among MOE which may find expression in the identification of MOE as belonging to a variety of mathematical

entities ranging from real numbers to semi-groups. They usually form posets although poset axioms can be selectively removed to produce more general rank orders which still correspond to "real world" MOE. As the MOE classification is successively generalized, the corresponding MOE should become correspondingly more inclusive and representative of the problem as a whole, rather than its constituents parts.

Some of the areas of mathematics which appear to bear on the MOE question are as follows:

a. Category theory for structure elucidation and problem comparison, especially of the modelling process.

b. Fuzzy set theory for its postulates that some data may be forever indeterminate to some degree.

c. Homotopy theory for its insights into how things transform and how they behave under general mapping arguments. Homotopy theory seems to have been neglected in its potential ramification for C/C in those instances wherein C/C can be visualized in terms of maps which carry orders from one set (the commander) to another set (the troops).

d. Lattice theory for its ability to handle relations arising from partially ordered sets (posets). (Order relations are the most common results of various committee procedures, and the lattice algebra is designed to do computations on numbers satisfying order relations.)

In summary then, an effort is being made to identify, and/or define the oft-used artiface known as the MOE. It appears that a number of interesting MOE are at least lattices and fuzzy sets. Now let us change the subject and become applications oriented, for it is in the context of applications that MOE must be recognized and manipulated. We look first at the world of computer based Army C/C.

3.0 A Case History. It may be isntructive to briefly discourse on the history of the Army's attempts to enter the tactical computer age for insights into the problems faced by proponents of total standarization. Such an incomplete sketch follows. Through the late 1960's and into the 1970's, the US Army identified various functional aspects of its tactical operation as candidates for automation. Some of the more important were as follows:

a. TACFIRE (Tactical Fire and Direction Control) for artillery;

b. TOS (Tactical Operating System) for use by division and brigade in the conduct of battlefield operations;

c. Various intelligence computers for use in the tactical environment; and

d. TSQ-73 for use in joint service air defense operations.

It might be expected that a computer-based C/C system would someday interconnect these machines.

The Army also had under development the SAM-D (now PATRIOT) air defense system which required its own generation tactical computer, and the CS_3 (Combat Service Support System) for use in rear area in performance of logistics functions.

Of the tactical systems, the TACFIRE was the first developed. A third generation, air-cooled machine, meeting field test conditions was developed under contract by Litton. It was the Litton L-3050 - later to be type classified as the AN/GYK-12. This general purpose, fixed point arithmetic machine had the capability to expand the command set to floating arithmetic. It also had a variety of I/0 devices designed for field operation. A language intended to be a subset of PL/1, called TACPOL, was developed. According to the terms of the original contract the equipment was to be designed so that various mass-production techniques could be invoked at various procurement levels to reduce unit cost. It can be argued that the AN/GYK-12 machine, or evolutionary variations of it, had the potential for being a first generation common computer system for all tactical uses. At issue were several

hundred computers.

As history was actually written, the L-3050 is being procured for TACFIRE and is completing tests for TSQ-73. TOS and the intelligence computers remain in the future except for demonstration configurations of TOS. Throughout this period of tactical computer development two management instruments were developed by the Army for control. One is the Army Tactical Data Systems Command. The other is the ATACCOMAP (Army Tactical Command and Control Master Plan).

The former is concerned with all development aspects of hardware and software for tactical uses. It has headquarters at Ft. Monmouth, New Jersey, home of the US Army Electronics Command. The other instrument, the ATACCOMAP, is basically a committee structure which oversees the periodic update of the Master Plan. Elements in the plan include, or have included, the following study efforts:

a. CONOPS - Continuity of Operations - (a control study).

b. EAD - Echelons Above Division - (a command structure study).

c. SYSCON - Communication Plan - (a communication study).

d. COMSR - Communications Support Requirements Study - (a communications study).

e. INTEROP - Interoperability of Systems - (a communications and control study).

f. CEATOS - A cost effectiveness of the TOS - (a command and control study).

g. IBCS (now TCC) - Integrated Battlefield Control System - (a control study).

h. INTACS - Integrated Tactical Commnications System (a communications and command study).

Inter-service efforts are monitored as well.

Although some liberty has been taken in assigning a particular study to one, or more, of the three C's, the overall conclusion must be one of extensive effort on all phases of the C/C

problem. There is no lack of MOE spread across all these projects. Problems arise when trying to draw conclusions across study lines using MOE developed for detailed individual studies.

Returning to question of the AN/GYK-12, we can perhaps extract some lessons:

a. The devlopment process is so long and slow; computer evolution, so rapid; that the users become disenchanted with machines under construction (in comparison with more recent prototypes) long before machines can be type classified.

b. Mass buys of complex systems, despite the well known cost learning curves benefits, are rarely possible.

c. C/C operations which have either a semi-automatic nature, or follow a fixed algorithm, or require extensive computation (e.g., nuclear fire planning) can be successfully fielded. (TACFIRE and TSQ-73 are examples).

d. The utility of the computer to more directly influence the battle is a slow process of definition which must be conducted with trial configurations in field exercises as well as in the laboratory.

It may be that unless the selection process is greatly accelerated, and the development of computers reaches some kind of plateau, the desired level of total standardization is not possible. If this perception has any validity a rather different viewpoint is necessary. In this regard it might be instructive to compare the development of telephone networking. Very standardized equipment in the pre-electronic days of cross bar switching is to be contrasted with current difficulty in making available the kinds of improvements and reductions in equipment size which electronics makes possible. There is an arguable viewpoint which accepts inherent complexity, and directs itself to measuring systems parameters which take into account a great diversity of equipment and procedures. Such a system viewpoint is not inherently impossible. It usually is not objectively examined for possible benefits. For

example, what is the trade-off that may be offered by the large number of combinations of pathways versus the probability of major component failure in a uniform system?

In summary then, the cultural matrix, in which the decisions leading to existing C/C systems together with the rapid pace of technology, may be such that a totally standardized system is not possible. Fundamental control of the C/C function may be through a committee structure which processes complex input in the absence of any theory of C/C. Committees need measures of total system performance rather than masses of detailed data in reaching their decisions.

4.0 A Matter of Perspective. Having become confounded by the complexity of the currently operating (and proposed) C/C systems, I have sought to extricate myself by escaping backward in time to some previous epoch. Can I find an era which was perhaps better understood, or which is capable of better understanding? In the search I asked myself the following question. Is this the best of all possible C/C worlds? Was there some time in the past when C/C hung together better than it does now? In order words, was there a time past when all the elements of C/C were present in a more complete form than today?

In such a halcyon time there would not only have been complete information, but excellent portrayal as well. A first analog that suggests itself is the World War II Command Centers in which ships and planes were represented by actual models moving across a large map. This is a kind of real time information display. It tends to replicate the situation pertaining when a commander sat on a hilltop with a spyglass and dispatched riders to the force in view. Let us reflect on this hilltop for a moment. Have we done better by retreating further? All the elements of good C/C seem at hand. Now let us again move forward in time.

As the size of the battle expanded out of sight, communications and control broke down. In a sense we can think of these as extensive and intensive aspects of the problem. The extensive

portion relates to the collection of needed information beyond the immediate senses of the commander. The intensive aspects is the volume of that information, and the integration of that information into a form suitable for real time decision making. The advent of radio restored the extensive aspect of C/C without necessarily restoring its intensive aspect. The proliferation of communications and intelligence links, and most recently the introduction of numerous and diverse battlefield sensors, has restored a protion of the intensive aspect. Yet information was, and is so intensive, that the senses are overwhelmed. The problem then becomes one of display and presentation capable of restoring an integrated picture.

The problem has a reciprocal element as well. It is addressed to the control of the forces. It is unquestionable that the personal charisma of the commander was a vital element in the execution of orders. As the commander receded from view so did the charisma. As communications were gradually upgraded, the written content of the messages got through, but not always the aura of command. Verbal message traffic restores some of the immediacy of command, but there are countervailing tendencies. Working to dilute this psychological immediacy is an increasingly complex and layered command structure, awash with data.

The problem is still not solved. There is ample evidence that very high echelons become involved in local engagements simply because the physical equipment permits it. Whether or not this is a surrogate for loss of effective overall control might be an interesting question. What is clear is this. Such loss of overall control is implicit in such local involvement. It seems that some of the testimony presented at the workshop is bound up with the inability of the current C/C to transmit various subliminal, but apparently essential, aspects of command down to the forces, e.g., esprit de corps.

Other interesting historical exercises might be to test some of our theories on World War I representing war as a steady state phenomena. Another interesting exercise is to examine C/C with no communication or overt control. This is the case when policy, preplanned or otherwise, is the element of control. In such cases control is embedded in the system. Too little time seems to be spent on constructing and understanding limiting cases in which one or two of the aspects of C^3 are eliminated. In a sense the trench warfare of World War I should be some kind of limiting case.

A little anthropology may also be instructive. Historically the pace of technical improvement has been very slow so that organizations responded organically to changes through empircal trial and error. Thus, the Eskimo culture represents thousands of years of empirical experimentation with all possible combinations of resources and strategies. Today, neither armies, nor cultures, have very much time to respond to the onslaught of change which is now the norm. Moreover, armies now work toward preventing combat while equipping and training for combat. The resulting chaos in the C/C is no less real than the resulting chaos when vastly improved techniques are introduced into static cultures. Some of the military complaints which I believe I have heard voiced at this workshop seem to have a familiar ring:

- Inability to communicate in the sense of understanding;
- Inability to cope with the formal structure;
- Excessive isolation of the higher decision maker;
- Unresponsiveness to change; and
- Failure to get the message out.

Because the idea of a time constant seems a natural way to describe complex time dependent physical phenomena, and because the question of time scales seems important to C/C, I have listed some classes of entities discussed in connection with C/C with their respective time scales for improvement and some estimate of current technical effort.

ENTITY	TIME SCALE	CURRENT TECHNICAL DEVELOPMENT EFFORT
Equipment for C/C	Months/Years	Excessive
Procedures for C/C	Years	Moderate
C/C Organizations	Years/Decades	Moderate
C/C personnel	Months/Years	Intensive*

* Development in the sense of training is implied.

I also note from this workship that a considerable bending of the human operator to fit equipment driven procedures is in progress.

I have also looked at the kinds of organizations which have C/C problems, and which might give insight into the C/C, as well as yield to analysis on the basis of time scales. The possible combinations are awesome.

TYPE OF ORGANIZATION

- Strategic
- Tactical
- Guerilla
- Task Force
- Police State

EACH MAY HAVE

STRUCTURE OF C/C IN ORGANIZATION

- Embedded in organization
- Explicit in organization
- Centralized in organization
- Distributed through organization
- Default
- Hierarchial

EACH MAY EXIST IN

SOME POSSIBLE STATES OF ACTIVITY

- War
- Peace
- Tension
- War through a surrogate

A proper theory of current C/C would distinguish combinations of the foregoing, as well as spell out their functioning. In a search for techniques which will yield insight, I would have to single out artificial intelligence (AI) as the area which heretofore has most often come to grips with the kind of C/C problems unearther in the workshop. AI seems capable of addressing the

dichotomy in C/C which says: "things as they seem" are as important as "things as they (actually) are." Ranking the three C's in order of indifferneсe to these two statements, I come up with the following:

AREA	"SEEM"	"ARE"
Communications	Indifferent	Very responsive
Control	Responsive	Responsive
Command	Very responsive	Less responsive

In regard to command, I might note that several speakers have mentioned the fact that commanders will make the same decision based on a wide variety of information, some of it contradictory and conflicting, when compared across the various commanders receiving the information. The message I am receiving is this. The current analysis thrust must be at understanding C/C as a total process. I might risk a physical compariosn to Boyle's Law. I find us in the stage before statistical mechanics when scientists sought to trace Avagadro's number of molecules in a room with Newton's equations...all $6.02 \cdot 10^{23}$ of them. Eventually we learned

$$PV = nRt$$

was as instructive as Newton's laws in dealing with ensembles. This seems to me the next step in C/C. If I had to sum up the need for MOE that semantically represented these ideas, it would be "plasticity."

Thank you for your attention and interest.

CLOSING REMARKS

by SETH BONDER
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My comments as a critique of the workshop have been formulated with respect to the objectives of the meeting, which can be stated as:

> observe the user command/control requirements and ongoing research activities, to ascertain where the research offices should encourage research that will be relevant to improving C^3 operations and/or planning.

During this meeting we have had broad and intermingled discussions of many facets of C^3 including:

(1) C^3 operations and related problems,

(2) planning problems for C^3,

(3) decision aids and related research to aid C^3 operations, and

(4) some theoretical research activities as candidate thoughts for use in analysis of C^3 operations.

The C^3 operational and planning problems were discussed in terms of various systems, procedures, organizations, and training. I would like to say that I have overlayed all of this information to:

(1) indicate the specific nature of the many C^3 operational and planning problems,

(2) indicate where existing theoretical results can be used to solve some of these problems, and

(3) point to areas where additional research efforts would be useful in addressing command and control problems.

I would like to say this--but can't since I have not done so. Instead, I have some general and specific observations, some of

which can be interpreted as recommendations, which I hope will be useful to the research offices sponsoring this workshop. In developing these comments, I have specifically kept in mind the tactical C^3 problems of the combat commander from the theater down to the battalion level and related Air Force command/control problems, which I believe to be the principle subject matter of the symposium rather than some of the strategic command/control problems addressed by a few of the speakers.

1.0 Structure of Tactical C^3 Problems. During the course of this workshop we had a number of users (e.g., General Welch, General Creech, Admiral Kinnear, Admiral Engen, Mr. Robinson, etc.) discuss many operational and planning C^3 problems. A sampling of these problems is given below.

Operational Problems

- o How can we ensure that operational decision makers continue to pursue a number cf hypotheses regarding enemy intentions, rather than focusing in on a single one too early? (Historical examples abound where the enemy has explicitly tried to reinforce a single false hypothesis.)
- o How can the success of an operational strike be determined?
- o How can the opetational commander ascertain the status of the battlefield?
- o How can decision making of operational commanders be improved?
- o How can a crisis in the making be detected?
- o What are appropriate courses of action to take to reduce crisis situations?
- o When is it appropriate to use the full command/control hierarchical net in a crisis situation, rather than direct linking to the NCA as has been the case in a number of recent crisis situations?

- o What is an appropriate manner to operate a C^3 net that is partially attritted or disrupted?
- o What are appropriate electronic warfare tactics to disrupt the command/control net? When should it be applied? Where should it be applied, against whom, and for what duration?

Planning Problems

- o What command/control phenomena should be included in methodology for examining the cost-effectiveness of different command/control systems, procedures, and organizations?
- o What criteria should be employed in making a cost-effectiveness assessment of a command/control system or trade-offs among elements of the system?
- o Should a system be designed with distributed or centralized data files?
- o What data should be made available to the various echelons of command? What is an appropriate organization structure of C^3 nets?
- o What responsibilities should be assigned and authorities delegated to various command levels in the C^3 net?
- o What procedure should be employed to assume reliable and timely responses from the command/control system?
- o What are appropriate training procedures for commanders?

Although the users and some analysts working in the area have an understanding of parts of the total command/control process and related problems, we did not have presented here a useful description of the tactical C^3 process that could be used to overlay the ongoing research activities. It is not at all clear that the user knows enought about this process to enunciate it in an organized fashion to accomplish the objectives of this workshop. The process is very complex and has many interactions within the C^3 process and between the C^3 and other processes in large scale campaigns. I think it would be fair to say that we do not have a military science of command/control processes. If the research

offices are serious about the objectives of this workshop then I would recommend that a paradigm of the C^3 process be developed that can be used to compare or checklist the C^3 operational and planning problem areas (systems, organizations, procedures, etc.) against the ongoing applied and theoretical research. I am confident that many such paradigms can be developed for the intended purpose. It seems reasonable to expect that the structure would be developed by a small combined user-analyst team or a small group of knowledgable analysts having ready access to appropriate users.

Research Activities

Although theoretical and applied research efforts have been presented in a number of diverse areas, it is clear that they are disjoint and that the objectives of this workshop have not, and a priori, could not have been accomplished. I believe this statement to be true for a number of reasons:

- As noted above, no organized way of looking at the C^3 problem areas was presented at this workshop.
- The research efforts presented at the workshop were somewhat disjoint and a structure for organizing ongoing research activities in a useful manner was not presented.
- Many relevant ongoing research efforts were not presented.
- It was clear that no communication/language mechanism existed between theoretical researchers and users (I believe General Creech made a similar observation).

It seems clear to me that a decoder is necessary to translate theoretical results (and activities) of the researcher and the requirements of the user into a common (probably analytic) language and then a matching of the research results and user requirements be made. Accordingly, I would recommend that the research offices conduct an analysis of the research efforts underway (categorize them, estimate the state of the art, etc.) and that these be matched with the C^3 problem areas to determine where

matchings exist, where research is needed, and priorities on these research needs. I hasten to add that the matching of theoretical research to user requirements is not a simple overlaying but rather a creative translation of abstract results and activities into areas where it can be usefully applied. Such an activity must be performed by persons knowledgable in both theoretical language and content and various aspects of the C^3 process.

2.0 Current Operational C^3 Problems. There exists some current and very important C^3 operational problems in Europe. Classification prohibits discussion of these at any length in this unclassified workshop. However, some of these were suggested by General Creech regarding the lack of basics of command/control in Europe and the vulnerability of the C^3 system. Although I know the problems cannot be solved by study alone, I think an intellectual examination of them by some of the bright minds represented in academia (analogous to the strategic studies conducted in the 1950's) would be useful. Perhaps the research offices could make some of this talent available directly to study organizations (e.g., Air Force Studies and Analysis) or through working seminars to address some of these operational problems specifically.

3.0 Decision Aids/Decision Makers. Yesterday we heard about some significant research and design efforts to assist the C^3 decision maker and to determine how to design systems that he can and will use in an operational setting. Clearly, this is a correct objective since the commanders will need assistance (he will be under an information overload, combat activities will be fast moving and complex, etc.) and a system should be designed so they can be used and are useful. It is equally clear that we, the analytical community, can provide aids that will be useful in a number of different ways. It seems to me that we can group decision aids into three decision classes:

(1) Inferential processing aids which can draw useful inferences from a large amount of detailed data. Pattern recognition techniques are an obvious example of this

type of aid, as are aids which point out negative inferences (e.g., an indication of when detections of two tank companies at different points in time could not, because of physical considerations, be construed as being the same tank company).

.2) Computational aids to provide the commander with effort, effectiveness, and risk information associated with different courses of action. Examples of this might include the revised PERT analysis of Professor Hartley, which might be used operationally to generate the distribution of the time for a large unit to move from point A to point B through a large transportation network. The combat result implications of different alternative force deployments is another example of this type of aid.

(3) Decision aids which automatically made good or "optimal" decisions in areas that require a very rapid response and are in a sense "not dramatically critical."

I personally believe there is a great need for, and that emphasis should be placed on, the development of aids in the first two categories with less emphasis on actual decision aids. Some of the latter should be developed in areas in which those decisions are already (or are in the process of being) automated, such as the allocation of field artillery batteries to targets in a fire direction center via the use of TACFIRE.

Presentations on the topic of decision aids and decision makers at this workshop might be classified into two categories. The first of these is research intended to develop an understanding of the decision making process. Examples of this type of research activity are the works presented by Dr. Modrick from Honeywell which tries to ascertain how commanders make decisions or the different styles of decision making and by Bob Andrews of ARI which tries to ascertain what information commanders do in fact use. I believe the intent of these types of research is to

learn how to design decision aids and systems that will be useful to commanders. The second category described in this workshop regards the use of decision aids (from my earlier definition) to assist the decision maker directly in making decisions or to train him in making better decisions. Efforts in these areas were described by Dr. Kelly of DDI and Dr. Weltman of Perceptronics, Inc.

Although both of these areas have some recognized value,[1] I don't believe they should be the principal approach pursued to improve the commanders decision making capability or to develop aids for the decision maker. I have a number of concerns regarding the first area of research (i.e., understanding the decision making process). I believe it is very difficult if not impossible to determine (infer) how decision makers make decisions and what information they will use in a particular situation. Secondly, it is not at all clear to me that we should be designing systems and aids based on data from commanders who have not had adequate experience or training in the use of such systems. For many reasons, I have concerns about automated "decision aids" for crisis management situations that are based on expected utility concepts or the training of decision makers to maximize the expected utility (or for that matter, the use of any other single model of the decision maker).

As previously noted, these research efforts do

(a) train decision makers via the use of a "decision maker model,"

(b) develop an understanding of the decision making process, and

(c) develop decision aids, per the talks presented at this symposium, which have some value in the overall training of decision makers and the design of inferential,

[1] Data for commander selection, development of graphics and appropriate interactive techniques, etc.

computational, and decision aids.

However, I believe (and I think past research results tend to support the hypothesis) that these objectives can be obtained by pursuing a very different approach--that of training decision makers via the concept of "guided experience." That is, we should train decision makers in the decision making activity by letting them practice decision making in simulated contexts with appropriate feedback, letting them observe the results and associated risks that are obtained as a function of their decisions. Although I have not had the time to think through the ramifications of this approach completely, it is clear that if offers a number of benefits, some of which are noted below:

- Commanders will learn to make "good" decisions by developing a better understanding of the complex processes they are supposed to control. It is well recognized that a not insignificant number of commanders do not understand the impact of modern technology and how it will or should influence the command function. In this context, commanders will learn about the ramifications (effectiveness, risks, etc.) of different decision choices; and this knowledge can be used in a personal manner when actual operational situations occur, rather than forcing decision practice into a particular mold of a stylized decision maker.

- Training of commanders via guided experience in simulated contexts can provide an appropriate experimental setting to determine where, in fact, aids will be useful to perspective commanders.

- Assuming adequate knowledge is available, through appropriate curricular design the guided experience approach can be used to show perspective commanders how to use information and computerized aids appropriately. Although I am not suggesting a Pavlov conditioning, in a

sense this approach will educate those who are unaware such aids can be useful and provide appropriate training with them.

- This mechanism of simulated decision making training can also provide an appropriate observation vehicle to determine the kinds and structure of decision making logic to incorporate into planning methods; i.e., large scale campaign models. The tendency today is to doctrine doctrine as stipulated in appropriate field manuals (rather than decision making behavior which is more likely to occur) or optimal decision making behavior based on the analyst's view of the world.
- Finally, such a guided experience training vehicle could serve an analysis function in that it will provide insight into the development of good tactics, resource allocations, command behavior, etc.

A number of systems have been developed recently that might be used for this purpose in selected areas. These include the Marine Corps Tactical Exercise Simulator and Evaluator (TESE) and the Army's Combined Arms Tactical Training System (CATTS). Neither of these systems have been used in the mode suggested above, but rather as procedural training vehicles to large sized command/control staffs. I believe they can simultaneously be used for individual decision making training per the approach above, although a number of research questions still need to be addressed to learn how to implement this approach sufficiently and effectively. These questions involve appropriate curriculum design to communicate and identify certain principals, the means of appropriately presenting information for learning (real, extended, or compressed time; error free or real information, etc.), the amount of "guided experience" required, etc.

4.0 Presented Theory. At this workshop a number of theoretical research activities were presented by some well known and extremely

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PROCEEDINGS OF THE WORKSHOP ON DECISION INFORMATION FOR TACTICA--ETC(U)

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capable researchers (Professors Hartley, Saaty, Gupta, etc.). As a former full time academic and now practicing analyst, I am sure I could identify some use (albeit small) of the theoretical efforts that would be related to command/control. However, I believe much of the theoretical efforts presented here miss the real target with respect to command/control problems. For example, as I previously noted, the work of Professor Hartley could be used as a computational aid to assist the commander in a mobility problem. However, it would be significantly more valuable from the command/control point of view to develop methods to assist in the design of "good" command/control networks and hierarchies and to determine how to operate them when the net is in a partially attritted or damaged state. My experience as a practitioner suggests that many of the interesting and important theoretical problems arise from the practice and are recognized by the practitioner. Although I understand the value and importance of supporting theoretical research in universities, the research offices should recognize that many practitioners are capable of working theoretical research problems, are interested in doing so, and can identify areas where critical needs exist. Usually the problem-oriented support for practitioners precludes any significant amount of abstract theoretical research. At a minimum, the research offices should develop a mechanism by which university researchers can interchange with appropriate practitioners on a frequent and regular basis.

I have a number of minor observations, however, it seems inappropriate to use any more of this valuable weekend time to present them. For similar reasons, I have not taken the time to highlight many of the valuable facets of this symposium/workshop. In conclusion we should recognize, as I have previously noted, that the objectives of the workshop have not, and, a priori, could not be accomplished. It has, however, served as an important vehicle for exchange of ideas and a means of verifying that, in fact, the problem which motivated the workshop does exist.

DISCUSSION

Hartley: This may be a very naive question. I think that I should address this to Dr. Bracken. He talked about the applications of game theory. I am a little bit puzzled about the application of game theory in an unclassified sense because this theory makes an assumption about an adversary behavior. If you reveal what kind of game theoretical model you are using, it is very simple for an adversary to behave in actually the opposite way than that theory would assume him to behave. There must be something that does not give away the third base coach signals.

Bracken: I have an answer to that. If one solves a game theoretical problem and one has full knowledge, regardless of what the opponet chooses, one is guaranteed to get at least that payoff. Now if one's opponent has full knowledge then he will indeed choose the optimal strategy. In any game of theoretical context, one is guaranteed at least the balance. General Kantor has pushed this concept pretty hard, took it over from Berkowitz and Dresher basically in the late 60's, termed the strategies mutua-ly enforceable which I think is a good group work. You can enforce any kind of strategy pick and if the other person doesn't pick his optimal strategy, he does worse, necessarily.

Dockery: We ran a class of simulations. The only one that we locked up and placed the computer on were things like nuclear strike which are very precise targets, very precise roles, very context dependent. The rest of what we run, depending on the data, may or may not be classified and then not very highly because we are essentially using information available on our side in the open literature asking what can happen to narrow the universe of possibilities. What actually will happen depends on the control and command that will be exercised at any given time.

Sovereign: It seems to me that there is an advantage in the game theory context in that you do find the boundaries and set examples. You have certain boundaries at certain times, for

example, when information is detrimental, in the sense that you have a mixed strategy. What you would like to do as a scientist is design a military force theory where you had a set of pure strategies so you don't have this worry about the information problems that lead to mixed strategies. I think there are certain principles that a military leader at the top of the command and control system is going to have to learn through examples like this and put them into a context of history. I think that type of course is what is needed in the war college and maybe in post graduate schools and other schools.

Coombs: I do want to point out the difference between the professional military education institutions, the war colleges, and the graduate education institutions, the Air Force Institution, the Naval post graduate school, in terms of role and rank of officers. I think that you said that top level people will quite a bit later after going through something like this, go to the college.

J. Thompson: I would like an estimate of the percentage of the dollars spent by DOD on large scale war games in a year or so which (1) have command capabilities and (2) have been validated? Do we have capabilities like Andrews suggested? Secondly, what percentage of military resources have been used for war games which have actually been validated using historical data?

Dockery: It is easier to answer the second question first. As you know, it has really been tested in the scientific sense and verifies actual data. This is a second model, forgetting those that are interactive. There have been some that have been tested against specific air defense models. Some of the work that has been done at Rand came under the samll little entry model. The Vietnamese time situation tested out purely wrong I think. The large scale, division and above, the AERO people, termed the computer, have done some work. They are not testing their models but are just trying to draw inferences from some statistical information. More importantly, since 1973 we can test the models

because the data has been collected. There is a compendium of data on the whole set of mideast campaign. It is sitting there and there is this opportunity to test at least one, two or three against them. There is not sufficient data in either of those cases to do that test because all the models do require some information that we do not even have.

Welch: Most of the decision level models at least in the past will show very sharp well moved capabilities based on force ratio. If you plot propensity to win versus force ratio, it will show a very sharp curve. Historical data refutes that almost exclusively. It says that when you are down 3 to 1 you still have a probability of 3 to 1 of losing. In that sense they have been tested. In my view my own conclusions from looking at those models is that by and large they do not include decision processes which account for that great disparity in test results. I think that because of this obvious random real data that indeed people did not go further.

Bonder: I know of two tests actually. One was done by STAG the predecessor of CAA (Concepts Analysis Agency) using ATLAS with the Korean War data. Atlas results did noatch the Korean War data. Another was done by the joint war games agencies to an Arab-Israeli War using Atlas again and it did not matche the Arab-Israeli war data. It is a computer model where the outputs are based on the force ratios and in the case of Korea that provided a good approximation in the case of the Arab-Israeli War it was not.

Question: The programs that don't work are those in which maneuver and such things are strong elements of the attack. The best one we can simulate would be trench warfare because of a perpetual stalemate. Those things in which maneuver is an element are done less well, less predictably and those which require control are just now beginning to be addressed.

Bonder: Your comments relate to the impact of command and control. I'm not sure if that is the only variable factor which

makes it work better. It is true that the command and control input changed some of the command behavior and the results changed dramatically. I have seen another division study where we got great divisional burdens after we used your outcast studies and some others where we just characterized the decision behavior to observe what would happen. It is a tremendous impact. That probably answers your first question.

The second question about how many are interactive, how you have war games with many players involved. There are a whole bunch of those which exist. The problem with them is, Jim, is that they just take too damn long to use. We are talking 6 months sometimes, 5-10 hours or more and you don't get a parametric analysis. What you get is a certain behavior of that game and it takes 6 months.

J. Thompson: I want to get something out of it. If we are not in the practice validating these models with historical data, I would at least like for them to be used in training.

Welch: I'll tell you what they are used for and that is equipment selection.

Bracken: The internal logic of the game is presumably defensible and they serve as a language about which to discuss trade-offs among weapons systems. In fact, they are the only language to talke about weapons systems with. Therefore, whenever there is an analytical study of the impact of the decison process it must be made in a language which is open and explicit and understood by all parties. Now, that is not to say that the poeple who make the decisions are necessarily bound by the recessive model, but it is the only consistent language that simulates interaction and takes everything into account and is an input into the decision process.

Question: Air defense weapons, o.k. In an equipment selection procedure, we look and make relative comparisons to the absolute question is brains. It involves bringing in the threat, the Soviet Pact air fleet aginst the Air defense of Western Europe.

In fact, that is an equipment selection process. There are simplifications as to the number of levels, but the weapons are turned loose. The game is played. Two runs are played a day. The officers go off into a corner and reconfigure the assets. We played a similar game and they came back on day 2, recongigure the assets after that. So we speed the ting up. What we are using it for is equipment selection and essentially it is the only game in town because the combinatorics are just out of sight.

Bonder: Jim, let me comment. Clearly, one can raise issues about degree of validity and degree of belief of assumptions, but as Jerry pointed out, it is the language in which you raise questions. You can say, I don't believe that assumption. At least you have something that you can agree to disagree about. Some of the basic policies are modelled reasonably well, maybe not verified on an unambiguous scale. It give you something to develop some insight with or at least get a point of discussion, but if you have someboyd with a closed mind and somebody drive through and say I see it and it's green. The discussion must stop. This is because there is nothing to talk about. This gives you something to question. I don't believe that assumption. I don't believe that data, let's hear how you came up of that data. Then let's come up with some new assumption. You can do that. I don't see any significant alternative to that problem.

J. Thompson: The main idea behind that, let me say, that we have some_ing incredibly more expensive, incredibly more complex with no real data validation behind it.

Bonder: We have computer assisted war games which a lot of the dice throwing and the implications of the decision are dumped into the computer. They make the decision before the course is treated, often, and does an hour or range. It gives you the results. You go up into a room and readjust it. You do the complete manual war game. I am saying that when the computer can do its job best and the major work, the setting of the track, the changing strategy to meet the effort that you have left off line.

Then the thing is re-submitted.

Welch: When all things are working in a historical situation, you have to be able to duplicate with considerable accuracy. A great many human factors, psychological factors, and skilled commanders are involved. Do you have that ability?

Bonder: That would be as complicated and would be a major undertaking which would only validate that particular model and your technique. I would not then trust it for a task worker anywhere else, but then I understand how to build such a models and that would be it.

J. Thompson: I can't agree with that. I don't see why you have to get a very good data about what is going on in the minds of the opposing generals in order to play your game.

Welch: Well, let me say what we did in probability may be interesting to you. I learned that there was a very simple method for large units when they feel surrounded, surrendered even though they don't have to. That seemed like a very useful thing to notice, and in fact, lead to some substantial requirements. It also lead to quite a number of other things which is to worry like hell about these fancy sensors that might determine what was the efficacy of that threat surrounding us. So ir seemed to me that those were at least two very straightforward lessons to learn.

Question: No, I wouldn't say we haven't validated sine we don't know where we are going to a degree. The simulations we're running went for 4 hours and we have a complete trace of every simple event generated stochastically by that. We then changed the statistical analysis. We have them examined by officers. We compare the individual operation with the test data. And that's the best that we've got. We've got absolute fine grain analysis. That the best we've got.

Question: Weapons selection are not made on the basis of your estimation of the cleverness of the people. The weapons selection is made on your estimate of the physical superiority of the

device you are vending.

Question: One of the commanders decides he is lost, independent of the actual situation. One might make a command and control point of looking at some of those battles, they can find out what information led to that conclusion.

VI. APPENDICES

PROGRAM

WORKSHOP ON DECISION INFORMATION FOR TACTICAL COMMAND AND CONTROL

22-25 September at Airlie House

SESSION I
Thursday 23 September 1976

0900 - 1230

Chairman: Dr. William L. Lehmann, Director, AFOSR

0900 - 1000	Major General Jasper A. Welch, Jr. Assistant Chief of Staff, Studies & Analysis Headquarters, U. S. Air Force "Key Notes on Decision Information for Tactical Command and Control: Desired Attributes of Command, Control, Communications and Intelligence"
1000 - 1100	Rear Admiral Donald D. Engen U. S. Navy Deputy Commander-in-Chief U. S. Naval Forces, Europe "Challenges of C^3 - Area of JCS"
1100 - 1130	Break
1130 - 1230	Dr. Thomas Saaty Wharton School University of Pennsylvania "Structures and Hierarchies"
1230 - 1400	Break

SESSION II

1400 - 1830

Chairman: Dr. William L. Lehmann, Director, AFOSR

1400 - 1500	Lt. General W. L. Creech, Commander, Headquarters, Electronics System Division (AFSC) Hanscom Air Force Base, Massachusetts "Decision Information For Tactical Air Forces Command and Control and Operation-Developer's View"
1500 - 1530	Break

1530 - 1630 Dr. James G. Miller, M.D., Ph.D.
President, University of Louisville
"Potential Applications of a General Theory of Living Systems To the Study of Military Tactical Command and Control"

1630 - 1730 Rear Admiral George E. R. (Gus) Kinnear, II
Chief of Legislative Affairs
U. S. Navy
"C^3 At Sea: A Commander's View"

1730 - 1830 Informal gathering at the "Stable Tavern"

1830 Dinner

SESSION III
Friday 24 September 1976

0900 - 1030

Chairman: Dr. Ismail N. Shimi
Directorate of Mathematical Sciences, AFOSR

Statistics Panel

Dr. S. Zacks
Chairman, Department of Mathematics and Statistics
Case Western Reserve University
"Some Statistical Problems in Logistics Research and Military Decision Processes"

Dr. Shanti S. Gupta
Department of Statistics
Purdue University

Dr. H. O. Hartley
Institute of Statistics
Texas A&M University

Dr. James R. Thompson
Department of Mathematical Sciences
Rice University

Dr. Harvey M. Wagner
Dean, School of Business Administration
University of North Carolina at Chapel Hill

General Discussion

1030 - 1100 Break

SESSION IV

1100 - 1230

Chairman: Dr. Robert L. Launer
Mathematics Division
U. S. Army Research Office

Mr. Robert Andrews, ARI
"Human Processes in Battlefield Information Systems"

Dr. John A. Modrick
Honeywell
"Decision Support In A Battlefield Environment"

Dr. Kenneth Homon
IBM
"The Lessons Learned in Translating Requirements Into Capability: The WWMCCS Architecture"

General Discussion

1230 - 1400 Lunch Break

SESSION V

1400 - 1530

Chairman: Commander K. C. Youngmann
NOP-943C1

Dr. Martin A. Tolcott, ONR
"New Approaches To Decision Aiding For A Naval Task Force Commander"

Dr. Clinton Kelly
Decisions and Designs, Inc.
"Decisions Analysis As An Aid In C^2"

Dr. Gershon Weltman
Perceptronics, Inc.
"Adaptive Computer-Aided Decision Systems"

General Discussion

1530 - 1600 Break

SESSION VI

1600 - 1800

Chairman: Major H. G. Hannah
HQMC (OTOS)

Dr. Donald Topmiller, W-P AFB
"Man-Machine C^3 Simulation Studies In The Air Force"

Mr. Robert F. Robinson, AF
"Desired Features For Modeling C^2 Information"

Colonel T. Thompson, TAFIG
"Case Study In Interoperability Management"

General Discussion

1900 Dinner

SESSION VII
Saturday 25 September 1976

0900 - 1030

Chairman: Commander K. C. Youngmann
NOP-943C1

Information and Cybernetics Panel

Dr. Thomas Saaty
Wharton School
University of Pennsylvania
"Hierarchies: Structure & Impact Analysis"

Dr. Clyde Coombs
Department of Psychology
University of Michigan

Dr. Robert M. Thrall
Department of Mathematical Sciences
Rice University

General Discussion

1030 - 1100 Break

SESSION VIII

1100 - 1230

Chairman: Lt. Col. R. A. Geesey, AF/SAGR

General Systems Panel

Dr. Robert Kalaba
Department of Economics & Biomedical Engineering
University of Southern California

a. "Team Decision Theory"
b. "Getting The Most From Decision Theory Research Dollars"

Dr. Thomas Hallam
Department of Mathematics
University of Georgia

Dr. Angelo Miele
Department of Mechanical Engineering
Rice University

General Discussion

1230 - 1330 Lunch Break

SESSION IX

1330 - 1545

Chairman: Colonel R. H. Stuart, AF/SAGR

Operations Research Panel

Dr. Seth Bonder
VECTOR Research, Inc.
Ann Arbor, Michigan

Dr. G. Bracken
Institute of Defense Analysis

Dr. J. Dockery
Concepts Analysis Agency

Dr. M. Sovereign
Naval Postgraduate School

General Discussion

1545 Closing Remarks: Dr. Robert M. Thrall
Robert M. Thrall & Associates

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The workshop on Decision Information for Tactical Command & Control was held at the Airlie House in VA on September 22-25, 1976. This workshop was sponsored by the AFOSR. There were approximately 200 participants from government, industry and the universities at the workshop. The workshop resulted in a volume of proceedings with the same title as the workshop. The workshop was considered an enormous success by many people who attended or received the final proceedings.